RECIRCULATING INDUSTRIAL AIR. THE IMPACT ON AIR COMPLIANCE AND WORKERS' SAFETY CASE STUDY HILL AIR FORCE BASE C-130 PAINTING OPERATIONS

By

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by

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Dedicated to
Cheryl, Michael and Nathan

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Abstract of Dissertation Presented to the Graduate School
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RECIRCULATING INDUSTRIAL AIR: THE IMPACT ON
AIR COMPLIANCE AND WORKERS' SAFETY
CASE STUDY: HILL AIR FORCE BASE C-130 PAINTING OPERATIONS

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The 1990 Clean Air Act Amendment resulted in new environmental regulations called the National Emission Standards for Hazardous Air Pollutants (NESHAPs). Industries such as painting facilities may have to treat large volumes of air, which drives the cost of an air control system. Recirculating a portion of the air back into the facility is an option to reduce the amount of air to be treated. A guided computer model written in Microsoft Excel 97® is developed to analyze worker safety and compliance costs with a focus on recirculation. The model has a chemical database containing over 1300 chemicals and requires inputs such as tasks performed, hazardous products used, and chemical make-up of the products. The model will predict indoor air concentrations in relation to occupational exposure limits (OELs).

A case study is performed on a C-130 aircraft painting facility at Hill AFB, UT The Aerospace NESHAP requires air pollution reductions in aircraft painting operations. The model predicts strontium chromate concentrations found in primer paints will reach 1000 times the OEL Strontium chromate and other solid particulates are nearly unaffected by recirculation because the air is filtered prior to recirculation. The next highest chemical, hexamethylene diisocyanate (HDI), increases from 2 6 to 10 5 times the OEL at 0% and 75% recirculation, respectively Due to the level of respiratory protection required for the strontium chromate, workers are well protected from the modest increases in concentrations caused by recirculating 75%. The initial cost of a VOC control system with no recirculation is $4 5 million and $1.8 million at 75% recirculation.

To decide the best operating conditions for a facility, all options such as product substitution, operational changes or recirculation should be explored. The model is an excellent tool to evaluate these options. At the Hill AFB facility, the model highlights strontium chromate primers as good candidates for substitution. It also helps determine a safe, cost-effective level of recirculation. The model shows that recirculating 75% of the air at the Hill AFB facility has a negligible impact on safety and could save $2.7 million on the initial expenses of a VOC control system.

CHAPTER 1
INTRODUCTION

The purpose of this study is to design and implement a computer model to assess recirculating industrial air back into an existing facility. Recirculating industrial air has received more attention recently because it can significantly cut the cost of complying with new environmental air regulations. This is particularly true when treating large volume airstreams containing dilute pollutants. The question that the computer model is designed to help answer is, "how much air can be safely recirculated without exposing the workers in the facility to unsafe conditions?" Depending on how much air is recirculated, chemical concentrations will increase to some degree due to recirculation. The model developed in this research will determine the incremental increase in chemical concentrations relative to varying levels of recirculated air. The model uses mass balance calculations and relates chemical concentrations to their respective occupational exposure limits (OELs) set by the Occupational Safety and Health Administration (OSHA) or the American Conference of Governmental Industrial Hygienists (ACGIH). A case study using a C-130 aircraft painting facility at Hill AFB, UT, is evaluated to demonstrate the use of the model. The chapters in this document and a brief description of each are organized as follows:

Chapter 1 (Introduction). This chapter provides a brief overview of the EPA and OSHA regulations surrounding the handling of industrial air. The concept of recirculation

will be discussed. A description of the recirculation model will be introduced. Also, the demonstration site at the Hill AFB painting facility will be discussed.

Chapter 2 (Literature Review). The history of cost/benefit analysis in governmental regulations is discussed. The conflict between the OSHA and the EPA involving handling industrial air emissions is reviewed. The need for a computer model to help decide how to handle industrial air safely and cost-effectively is examined.

Chapter 3 (Theories and Assumptions). Derivations of the formulas used in the model to predict air concentrations and air control costs are presented along with a discussion of the associated assumptions.

Chapter 4 (About The Model). A detailed user's manual for the computer model is provided. All input variables and output data used by the model are discussed.

Chapter 5 (Case Study). The various tasks and products used at the Hill AFB C-130 Painting Operations demonstration site are described in detail. Insight is provided on how to model a facility and how to determine which input variables are required.

Chapter 6 (Model Validation). The validation procedures performed on various parts of the model are presented. Vendors provided price quotes, which are compared to the model's cost predictions. Actual on-site air sampling results are compared to the model's air concentration predictions. Finally, a Monte Carlo[1] sensitivity analysis and a qualitative sensitivity analysis are used to assess the relative importance of different variables on the model's predictions.

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[1] Monte Carlo is a technique where distributions are assigned to selected variables to determine the probability of a range of outcomes. The impact of each variable on the outcome can then be assessed. Software called Crystal Ball is used in this analysis.

Chapter 7 (Results and Conclusions) The model's outputs for the Hill AFB painting facility are discussed. Recommendations and conclusions based on these outputs are also provided

EPA--1990 Clean Air Act Amendments

The 1990 Clean Air Act Amendments (CAAA) signed into law by President Bush on November 15 1990, took a new direction in the regulation of industrial hazardous air pollutants (HAPs) In 1990, Congress had become impatient over the fact that the EPA had only regulated 7 HAPs in 25 years. The 1990 CAAA requires the EPA to regulate air emissions of 189 specified chemicals (HAP list) The EPA is required to regulate any facility that produces over 25 tons/year from the HAP list or over 10 tons/year of any individual chemical on the HAP list by the year 2000 (Sexton, 1995 218) The EPA is also required to add 25 new chemicals to the list every three years starting from 1990 (Elsevier 1995 214). The approach taken by the EPA is to regulate all major industries that produce large quantities of HAP emissions. Each facility is required to follow the industry specific regulations known collectively as the National Emission Standards for Hazardous Air Pollutants (NESHAPs) As an example, the U S Air Force is largely impacted by the "Aerospace Manufacturing and Rework" NESHAP, which regulates any facility which performs construction or maintenance on an aircraft.

In general, each NESHAP requires that everyone in the industry must comply with the Maximum Achievable Control Technology (MACT). The MACT is based on the average air pollutant emissions from the cleanest 12% of the industry without consideration to the actual risk posed by the pollutants. In other words, the dirtier

facilities in each industry must become as clean as the facilities with the least amount of HAP emissions (Hughes et al., 1994).

Recirculation

In many workplaces, OSHA regulations require a minimum air velocity in order to keep pollutants away from a worker's breathing zone. If an industrial facility has a large volume, a minimum velocity results in a large airflow. This large airflow may have a dilute concentration of pollutants. Airflow is a major factor in the cost of an air treatment control device. A large airflow is anticipated to be expensive in trying to comply with the new NESHAP regulations. For example, a small paint facility at Travis AFB, CA, with a flow rate of 30,000 cfm is estimated to cost $400,000 annually using thermal incineration as an air control device (Hughes et al., 1994, 85).

The NESHAP regulations have made the idea of recirculating some fraction of the exhaust air back through a facility very appealing. Recirculation will reduce the airflow to be treated, which will reduce the size and cost of the treatment system. If, for example, 50% of the exhaust air is filtered and recirculated back into the facility then only the remaining 50% is left for treatment and the cost is nearly cut in half. There is an added benefit of reduced heating or cooling costs because the loss of climate controlled air will be reduced. Recirculation will also allow the air velocity, required by OSHA, to remain unchanged. An illustration of the recirculation concept is shown in figure 1.1.

OSHA Regulations

One way of looking at recirculation is that it is a tradeoff between two federal agencies designed to protect different populations. Basically, OSHA prefers to move

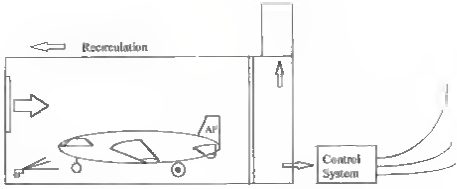


Figure 1-1 Recirculation Concept

pollutants outdoors away from a worker's breathing zone The EPA regulations influence industry to contain pollutants indoors or away from the outside environment and the local population. There is understandable reluctance to recirculate industrial air from the perspective of industrial hygiene personnel whose job is to keep employees safe from occupational exposures

With recirculation, workers in a facility could potentially be exposed to higher levels of pollutants. OSHA regulations require that no worker shall be exposed to chemical concentrations above a specified OEL. In this study, chemical concentrations are computed at various recirculation levels and the concentrations will be compared to the OEL for each chemical.

There are other philosophical questions For example, are OSHA exposure limits more or less protective than EPA environmental limits? Due to differences in risk philosophy, EPA limits are generally considered more protective than OSHA limits (Sexton 214) Recirculated industrial air may increase worker exposure to some degree but there is a tradeoff with cost, environmental pollution and risk to people living near the

facility. Also, a decision-maker who is considering recirculation must determine how much of an increase in indoor air concentrations is high enough to cause concern for workers in the facility. Decisions concerning worker safety are made by industrial hygiene personnel who may differ in professional judgement. There is also the consideration that workers can be protected with respirators whereas the environment or the public can not be protected in this fashion. Some argue that workers volunteer to work in a facility and therefore accept and are paid for the risk of the job. Others argue that workers often have little choice and concentrations in a workplace are substantially higher than in the environment.

It is easy to see that there are many influences to redesigning an air treatment system and a thorough case-by-case analysis is required to assist decision-makers with choices for a given facility. This study will not be able to address all these issues but the important quantifiable issues will be addressed. The final decision is always up to the decision-maker. The model developed in this research offers a valuable tool to understand the confusing array of multiple variables and multiple objectives.

The Model

The purpose of this study is to develop a computer model to balance worker safety and air control costs to help determine what level of recirculation, if any, is safe and cost effective. The model will also help with other choices such as product substitutions or operational changes that could facilitate EPA and OSHA compliance. The computer model has been built in Microsoft Excel 97 ® (henceforth referred to as Excel) and inputs are entered through Visual Basic for Applications ® (VBA). The user must run the model

on Excel 97 or higher. A 90MHz Pentium with at least 16 Megabytes of RAM is required to run the model at a tolerable speed. The user loads specific information such as the types of task performed in the facility and the types of products used in those tasks. Other inputs such as the usage rates of each product and the chemical breakdown of each product are also required. The model uses mass balance calculations to compute indoor air concentrations for each chemical under different recirculation scenarios (see Chapter 3 for calculations). The model will then vary the degree of recirculation and output the air concentrations, fire hazards, control costs, and a variety of other outputs (see Chapter 4 for how to use the model).

U.S. Air Force Problem

A case study was selected to demonstrate the model and to help determine how much recirculation is reasonable for a specific Air Force painting facility at Hill AFB, UT. The Air Force has several large-scale depot facilities that overhaul aircraft and aircraft support systems at regularly scheduled intervals. Military aircraft require re-painting at time intervals dependent on the aircraft type. Often the frequency of the protective coating applications is required for each aircraft due to safety concerns. There is currently no good substitute for the primer undercoat with polyurethane topcoat paint system required of most aircraft although better paint systems are being researched (Ayer and Wolbach, 1988).

Hill AFB is in Salt Lake City, UT. The C-130 painting facility (building 270) at Hill AFB paints about 50 C-130 cargo planes per year to include both Air Force and Navy aircraft. In 40 CFR 63.745, which is part of the "Aerospace Manufacturing and Rework"

NESHAPs (U S EPA, 1995), it stipulates that existing aircraft painting facilities must recapture 81% of the volatile organic compounds (VOCs) emitted by the facility (95% for new facilities) VOCs have been blamed for producing photochemical smog and the creation of tropospheric ozone, which can exacerbate upper respiratory ailments and make breathing difficult for asthmatics (Whitfield, 1995) Based on calculations of the products used, the C-130 paint facility consumes about 34,000 lbs. of VOCs per year and currently the exhaust is simply filtered and released to the environment The VOCs are largely found as a solvent in the approved paints and cleaners that are used to paint the aircraft.

The generally accepted air control system for VOCs is some form of thermal destruction. The paint booth is 100 x 100 x 30 feet and OSHA requires a velocity of 100 feet/min in paint facilities, which creates 355,000 ft^3/min of airflow (Ayer and Hyde, 1990, Parsons, 1995) Without recirculation, the cost of VOC removal using thermal destruction at this flow rate is estimated to be about $5 million in capital expenses and $200,000 annually even with the most efficient thermal destruction system (see Chapter 6 vendor quotes) Compliance of the "Aerospace Manufacturing and Rework" NESHAP rule is required by Sept 1, 1998 (Hughes et al., 1994)

Goals and Objectives

The four major objectives in this research are as follows.

1 Develop computer model to help decision-makers decide what level of recirculated air is cost-effective and safe

2 Evaluate Hill AFB painting operations to help decide how to safely comply with new "Aerospace Manufacturing and Rework" NESHAP Laws

3 Provide air sampling screening tool and product substitution evaluation tool for industrial hygiene personnel.

4. Merge knowledge from the following variety of disciplines into one computer model to include elements of risk assessment, air control, toxicology, fate and transport chemistry, probability theory, EPA/OSHA regulations, industrial hygiene principles, environmental engineering principles, ventilation systems, economic principles, painting operations and computer programming

CHAPTER 2
LITERATURE REVIEW

Introduction

This chapter will begin with a brief discussion of cost/benefit analysis in governmental regulations, which gives a better understanding of the influences behind this study. Then, the issues surrounding how to handle industrial air emissions from a facility will be discussed. The need for a computer model to help decide how to handle industrial air safely and cost-effectively will then be explored.

This study is inspired by the recent emphasis on cost/benefit risk assessment in governmental regulations and by observing competing objectives among federal agencies such as OSHA and EPA. Both OSHA and EPA are chartered to minimize different aspects of human health risk. OSHA protects workers from pollutants in the workplace and the EPA protects the general public from pollutants often emitted from the workplace. In complying with OSHA regulations, there is a tendency to get pollutants out of the workplace. In complying with EPA regulations, there is a tendency to contain pollutants indoors to reduce emissions from the workplace. These objectives can conflict and a specific example involving the EPA's CAAA and OSHA's Occupational Exposure Standards will be explored in this study.

Cost/Benefit Risk Assessment

The concept of cost-benefit analysis (CB) and risk assessment (RA) is used in many industries as a way of optimizing expenditures on a finite amount of money in order to do the most good. CB/RA is a technique to compare and optimize alternatives by calculating the cost and the potential benefit of each alternative. If spending $1 million on disease A will save 10,000 lives per year and spending the $1 million on disease B saves 100 lives per year, putting more money towards disease A gets the greatest "bang for the buck." Decisions are never this clean because of quality of life issues, uneven distribution of benefits or costs, different probabilities of success and uncertainties etc. However, this concept can be applied to some degree to obtain the greatest public benefit with a fixed amount of money.

Congress has recently become more aware of the virtues of CB/RA to measure the impact of federal regulations. CB/RA has received a great deal of discussion in recent legislative history. Debates over the past few years have focused heavily on using CB/RA in environmental regulations. In 1994, at least a dozen new amendments were introduced to mandating the use of CB/RA (Davies 5). However, many of these amendments were marginally voted down in the House of Representatives due to disagreement over approach and pressures from environmental groups who feared that the new legislation would dismantle environmental efforts. A few highlights are as follows.

- 1987 – landmark report Unfinished Business written at EPA's request – recommended the use of risk assessment in government regulations (Clarke, 1995 67),
- 1990 – Scientific Advisory Board (SAB) prepares report Reducing Risk, Setting Priorities and Strategies for Environmental Protection urged setting priorities using risk reduction (Clarke, 1995 67).

- Spring, 1993 – amendment to require CB/RA into all environmental regulations (defeated) (U S House 1993).
- October 4, 1993 – President Clinton s Executive Order 12866 – introduce CB/RA into all government agencies (Davies, 1995 5),
- May 1994 – Safe Drinking Water Act required EPA to perform a CB/RA for proposed drinking water regulations costing over $100 million (defeated) (U S House, 1995)
- October 7 1994 – The Risk Assessment Improvement Act of 1994 (defeated) (U S House, 1994).
- Jan 1, 1995 – "Contract With America" required regulatory reform to include CB/RA (U S House, 1995).
- Jan 1995 – Public opinion polls show over 80% of the Americans desires some form of CB/RA (U S House, 1995) and
- Feb 2,1995 – The Department of Energy (DOE) Risk Management Act required the EPA to perform a CB/RA for all proposed DOE clean-up tasks (defeated) (U S. House, 1995)

CB/RA has received increased attention due in part to the general criticism that funds and effort are not distributed in proportion to the magnitude and severity of the risk involved. CB/RA is seen as a way of using science and economics to better distribute limited funding sources to obtain the greatest overall benefit (Panel, 1995 54) Currently, priorities vary widely between spending large amounts on problems with little benefit to spending little on problems with potentially large benefits. It is estimated that the annual cost of risk regulations is $600 billion and the costs are rising at double digit rates (Graham, 1995 62) Several reports suggest that a lot of money is being spent as a result of specific environmental regulations, with negligible benefits, especially when compared to other public health regulations. One study done at Harvard University suggests an additional 60,000 U S citizens would be saved each year if resources are allocated more evenly across risk reduction programs (Clarke, 1995 65)

One study computes the dollars spent per statistical life-year saved for 500 different government interventions. The median government intervention cost is $42,000/life-year saved By comparison, the average medical intervention cost is

$19,000/life-year saved and the average toxic control intervention is $2 8 million/life-year saved ($4 2 million for EPA toxic control and $1 4 million for OSHA toxic control) (Tengs et al., 1995) The range in the amount of money spent per life-year saved varies tremendously over 11 orders of magnitude within nearly every federal agency The cost per life-year saved ranged from an intervention paying for itself (zero cost) as in driver school programs to an intervention costing $99 billion/life-year saved as in the chloroform private well emission standard at 48 paper mills. The actual dollar amount spent may not necessarily be as high as $99 billion but the benefit of life-year saved (the denominator) may be very small (Tengs et al., 1995 369) Another study analyzed data from asbestos product bans, NESHAP rules and pesticide bans. This study derives a cost of $45 million per statistical life from the cost of the pesticide and asbestos bans (Van Houtven and Cooper, 1994 18)

One explanation for the wide range in dollars spent per benefit gained is the avoidance of Congress to legislate how risk assessment is performed or even to establish priorities. Congress has in the past included generic implications in laws such as "below a reasonable risk" or "as low as reasonably achievable" but these are left up to broad interpretation and open to litigation in the courts (Clarke, 1995 67) In fact, most major pieces of environmental legislation ignore CB/RA all together Only two environmental statutes the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) and the Toxic Substances Control Act (TSCA) actually require that the cost and benefits of regulations be balanced in setting standards (VanHoutven, 1994 1). The 1990 CAAA specifically requires that the Maximum Achievable Control Technology (MACT) be used as a standard, which is not directly related to the actual risk posed by an industry (Hughes et

al., 1994; Davies, 1995) The MACT is based on an industries current pollution control technologies rather than pollution control based on risk The MACT will be described in more detail below

Problems with Cost/Benefit Risk Assessment

The concept behind CB/RA is to compute the costs and the benefits of alternatives. Then, the alternatives with the lowest cost/benefit ratio become the most desirable options In the case of recirculating industrial air one could compute the costs and the benefits at each level of recirculation to see which level of recirculation has the lowest cost/benefit ratio With all things being equal, as recirculation increases there is a benefit to the local environment and people surrounding the industrial site However, as recirculation increases, there is also a loss of benefit to the workers as potential chemical exposures increase and workers bear more burden of risk.

With respect to the cost side of recirculation, there is a net savings as recirculation is increased because there is less air to treat which drives down cost. One could theoretically develop an algorithm that would compute the cost/benefit ratio of this problem to see what level of recirculation is cost effective However, this approach is flawed because by increasing recirculation there is a small benefit to local people (large population size) offset by a larger loss of benefit to workers (small population size) The analysis may become skewed to placing more burden of risk onto workers because there are fewer people impacted. The problem is not as simple as "the good of the many outweigh the good of the few" because of the potentially disproportionate risk that would be placed on workers This could mathematically translate into recirculate 100% of the air

to drive costs down for the benefit of the larger local population while burdening the workers with all the risk because there are fewer lives at stake

There are other difficulties in using CB/RA when considering a decision on recirculating industrial air One of the benefits of the CAAA is controlling VOCs. VOCs are blamed for creating tropospheric ozone which impacts people with breathing disorders (Whitfield, 1995) This benefit has more to do with quality of life than a quantifiable benefit like life-saved While there is a death rate associated with tropospheric ozone, a primary benefit is reduced respiratory disorders or increased visibility These types of benefits do not lend themselves well to a quantifiable CB/RA. Although it should be mentioned that controlling VOCs is used as an enforceable surrogate to control a variety of other HAP's that are emitted from an industry The hope is that by controlling the broad category of VOCs, individual HAP emissions will also be controlled

Another difficulty in performing cost/benefit risk assessment on recirculating industrial air is OSHA exposure limits set for workplace safety are only a "do not exceed" level and they do not lend themselves to a scaled benefit. OSHA permissible exposure limits are set so that a worker can be exposed for a 40-hour workweek without deleterious health effects In other words, reducing a workers exposure from 100 mg/m^3 to 50 mg/m^3 does not make the benefit to the worker twice as good according to OSHA philosophy Unlike EPA cancer slopes, which are assumed to have a dose-response relationship, OSHA limits are not assumed to have a linear dose-response relationship, which would be needed to perform a true CB/RA.

OSHA versus EPA

Another complication to comparing risk between workers protected by the OSHA and local populations protected by the EPA is there is a difference in what is considered a safe level of exposure. EPA "safe levels" generally tend to be more stringent than OSHA's exposure limits. In fact, a study sponsored by the EPA determines the "safe" concentration of a large variety of chemicals based on the standard EPA Risk Assessment Guidelines (RAGs). In this study safe is defined as the concentration that would result in a one in a million excess life-time cancer risk or a hazard index of one. These benchmarks are generally considered to be safe. EPA default parameters and calculations were used to determine the safe air concentrations (Smith, 1990). Table 2-1 illustrates a random selection of chemicals with the computed EPA safe concentrations compared against the OSHA and the ACGIH OELs. All units are in ug/m^3 and "C" indicates a ceiling limit. All the rest of the OSHA limits are time weighted averages (TWA). The last column is a ratio of the OSHA limit versus the EPA limit.

Table 2-1 OSHA versus EPA Limits

	ACGIH (ug/m^3)	OSHA (ug/m^3)	EPA (ug/m^3)	OSHA/EPA (ratio)
Chromium VI Compounds	0.5	C 100	0.00015	666,666
Hexamethylene diisocyanate	34	34	0.01	3400
Methyl isobutyl ketone	205,000	410,000	84	4881
Methyl ethyl ketone	590,000	590,000	1000	590
Toluene	188,000	750,000	420	1786

There are legitimate reasons for differences between OSHA and EPA safe levels. Workers are typically healthy adults, whereas the demographics of the local population

may include children, elderly and immune-deficient people. Therefore, the local population may need additional protection due to a more vulnerable sub-population. Also, EPA assumes a lifetime of constant exposure (630 000 hours in a 75 year life time) where OSHA only considers a working lifetime of 40 hours per week ($0,000 work hours in a 40 year working lifetime). However, the limits that are considered safe often vary by 4 orders of magnitude which is not fully accounted for by these differences.

Modified Cost/Benefit Risk Assessment

Because of the problems explained above, the approach taken in this study will be to comply with the CAAA in a cost-effective manner without posing undue risk to workers in the workplace. Instead of using the approach that places local population risk into conflict with workers' risk, the approach will be to assume that compliance with the CAAA implies a satisfactory level of safety for the environment and the people in the local area. It is also assumed that compliance with OSHA worker safety regulations implies a satisfactory level of safety for the workers. This approach will determine the level at which industrial air can be recirculated to comply with both the EPA and OSHA regulations while keeping air control costs as low as possible.

Economic Section

The air control costs are computed using EPAs COST AIR model. COST AIR was designed by the EPA to estimate the cost of an air control system under any one of eight different control technologies (Vatavuk, 1989). From these eight control technologies, three of the more common thermal control technologies have been selected for the economic section of this model. Thermal treatment is selected because it is

generally used for organic compounds, which are often involved in air pollution control (Yevshenko, 1996; Venkatesh et al., 1997). The three control technologies are listed below:

1. Regenerative Thermal Oxidizer (RTO) with Carbon Adsorption Concentrator,
2. RTO Only, and
3. Thermal Incineration.

Each of these technologies relies on thermal destruction. The main difference between thermal incineration and an RTO is in the use of a heat exchanger. The RTO recycles more of the heat so that less fuel is needed. The capital costs for an RTO are higher but the operating costs are less because the RTO uses less fuel. Generally, for a large airflow, the most cost effective control is the RTO combined with a carbon adsorption concentrator. When RTO is combined with carbon adsorption, even less fuel is needed because the carbon adsorption will concentrate the pollutants. A smaller, less expensive RTO is needed with a carbon adsorber but additional capital expenses will be required for the carbon adsorber. Selecting an air control device becomes a choice of paying more up front for less costly annual expenses in the future (Brooks, 1994). The model assumes a 10-year life cycle for each system and over that time the RTO with carbon adsorption is the best choice at high air flow rates. However, at lower flow rates there may be times when the other systems will be less expensive and hence they are also included in the model.

The annual cost for each technology will be plotted against various levels of recirculation. Even though all three technologies are considered, the technology with the lowest life cycle cost would logically be the one that is implemented. A full explanation of

all the assumptions and theories in the COST AIR models will not be discussed in this document as they are already detailed in the EPA COST-AIR Control Cost Manual (Vatavuk, 1989) However some of the assumptions and theories will be discussed in chapter 3

Workers' Risk

The risk to workers in the workplace will be based on the indoor concentrations of each chemical relative to the occupational exposure limits (OELs) set by OSHA, ACGIH or both. There are published OELs for each hazardous chemical that OSHA regulates. One type of OEL is the permissible exposure limit (PEL), which requires that the daily exposure to a chemical shall not exceed the PEL on an 8-hour time weighted average (TWA) basis Another type of OEL is the ceiling limit, which is designed as an upper limit of exposure that can not be exceeded at any time during the day The short term exposure limit (STEL) is another type of OEL, which allows exposure up to the STEL concentration for 15 minutes not to exceed four times a day Because STELs are so similar to ceiling limits, STELs are treated like ceiling limits in the model If a chemical has a STEL instead of a ceiling limit the maximum predicted indoor concentration will be compared to the STEL even if the exposure is less than four times a day for less than 15 minutes each.

There are other organizations that also publish OELs such as the ACGIH ACGIH publishes Threshold Limit Value–Time Weighted Averages (TLV–TWAs) which are the equivalent of the OSHA PELs They also publish TLV-STELs and TLV–Ceilings, which are also equivalent to OSHA's STELs and ceilings. While OSHA is the only legally enforceable entity, the values from ACGIH and other organizations are sometimes used as

a conservative approach in the field of industrial hygiene when evaluating worker safety. In fact, according to Air Force Occupational Safety and Health Standard 48-8 paragraph 4.2 (AFOSH 48-8, 1994), " the OEL using the most stringent limits from these three references OSHA PELs, ACGIH TLVs, and other AFOSH Standards... shall be used to evaluate workplace chemical exposures." AFOSH can establish additional safety standards for the Air Force as long as they are at least as stringent as OSHA.

OSHA and Recirculation

The concept of recirculating indoor air has long been seen as a cost saving method mainly to conserve the heating or cooling costs of a building. Most structures have some level of recirculation and some level of fresh make-up air when the indoor air is thermally controlled. A great deal of attention has been paid to determining what level of recirculated air versus fresh air is appropriate. From a cost saving point of view, one would want to recirculate 100% of the indoor air, which some building managers may be tempted to do. However, health and comfort problems such as elevated levels of pathogens, chemicals or carbon dioxide can cause drowsiness, discomfort or illnesses to the occupants. If chemicals are used in the facility and concentrations of pollutants build up due to poor ventilation, the indoor air quality can reach dangerous levels. Sick building syndrome or tight building syndrome are terms coined for buildings that suffer from poor ventilation resulting in poor indoor air quality. Often the solution for these problems is to simply increase fresh air or treat the recirculated air to reduce pollutants. Other industrial facilities may require more fresh air depending on the type of activities performed in the

building. Hospitals, for example, require various levels of fresh air depending on the use of the room. An operating room requires at least 15 air changes per hour (ACH) to maintain sterility and reduce concentrations of infectious diseases versus a waiting area which only requires 4 ACH.

OSHA regulates industry with a heavy reliance on ventilation to keep harmful concentrations of chemicals and pathogens below levels that will effect humans. Up until 1985, OSHA had specifically banned the use of recirculation in spraying operations in accordance to 29 CFR 1910.107 paragraph (d)(9) (OSHA, 1997a). This regulation was adopted from the National Fire Protection Association Code 33 (NFPA-33) for fire protection. NFPA-33 was written in 1969 and is titled "Standard for Spray Finishing Using Flammable and Combustible Material". The NFPA-33 code updated in 1985 allows recirculation under certain conditions but OSHA has not yet updated 29 CFR 1910.107 (OSHA, 1997a). Under OSHA's policy for "de minimus violations," OSHA allows a company to comply with the most current standards and therefore has allowed compliance with the NFPA-33, 1985. Several interpretation letters have been written by OSHA indicating this policy change (Hughes et al., 1994, Clark, 1991). The NFPA-33, 1985 basically allows for the use of recirculation as long as all hazardous chemical exposures are held below OSHA OELs and the indoor air concentrations are held below 25% of the lower explosive limit (LEL). There are other requirements such as the use of continuous monitoring devices but these are the main features found in NFPA-33. 1985 paragraph 5-6.1. There is also a new standard from the American National Standards Institute (ANSI) for Industrial Process Exhaust Systems, which addresses the proper use of recirculation in industry. The draft ANSI standard states "all possible combinations of base materials and

the materials that can be created during the process shall be researched and documented before recirculation is considered" (ANSI, 1997)

Other Industrial Recirculation Systems

The Deere Company in Davenport, Iowa, installed and patented a paint booth recirculation system as far back as 1981 mainly due to the energy crisis in the late 70s. The system recycled 90% of the air but the environment was not considered safe for workers without respirators so air pressurized hoods were given to all workers (occupational limits were more liberal in 1981) Also, the LEL was a concern so alarms and automatic dampers were installed to allow the system to return to 100% fresh air if concentrations built up to 25% of the LEL (Norton et al., 1984) One of the first Department of Defense recirculation systems studied was for a paint booth installed at the Marine Corp Logistics Base (MCLB) in Barstow, CA The system uses HEPA filters and UV oxidation to destroy VOCs and is still in operation today (Watt, 1995 150).

A study sponsored by the Environics Lab, Tyndall AFB, FL, was performed in 1992 at Travis AFB CA, where an existing paint booth was modified to recirculate 50% of the exhaust air Air sampling in the paint booth suggests that recirculation could be implemented without exceeding OSHA established safe levels for workers (Hughes et al., 1994) However the quantity of paint used in this study was small and does not reflect the quantity, product type or application rates of another facility

Another recirculation system is installed at Hill AFB building 515 to study a split-flow recirculation design and the effectiveness of VOC destruction systems (Ayer and Hyde, 1990) A split-flow design takes advantage of recirculating the upper portion of air,

which generally has lower air concentrations. A recirculation rate of 50% was established at the Hill AFB building 515 painting facility. However, a safe recirculation level is dependent on the type of products used and how they are used among many other variables and each facility should be investigated on a case by case basis.

Impact of CAAA on Air Force

As mentioned before, the 1990 CAAA gave birth to a new set of EPA regulations collectively known as the National Emission Standards for Hazardous Air Pollutants (NESHAPs). The CAAA required the EPA to regulate all industries that output over 10 tons/year of any chemical (or a total of 25 tons/year collectively) from a list of 189 chemicals handed down by Congress known as the "189 HAP List." The EPA has until 2000 to regulate each industry that emits this level of pollutants. (Elsevier, 1995: 214)

The NESHAP that will have a large impact on the Air Force is called the "Aerospace Manufacturing and Rework" NESHAPs (U.S. EPA, 1995). The final rule for the "Aerospace Manufacturing and Rework" NESHAP was published September 1, 1995, and industries affected have three years to comply (Sept. 1, 1998). This regulation will effect 2,800 major military and commercial aerospace facilities (Elsevier, 1995: 214).

The section that will be specifically addressed in this research is the Standards for Primer and Topcoat Application Operations (40 CFR 63.745(b)). This section of the regulation stipulates that existing aircraft painting facilities must recapture 81% of the VOCs emitted by existing facilities (95% for new facilities). VOCs are used as a surrogate for other pollutants created from aircraft painting operations. It would be difficult to regulate the industry on a chemical by chemical basis, so the EPA uses VOC recapture and

high efficiency filtration as a way to control the emissions. The assumption is by controlling VOCs to a specified level and by using efficient filtration, other HAP emissions will also be controlled

The airflow through aircraft paint facilities is quite large Airflow is a main determinant in air control costs for VOCs because VOCs are generally destroyed by burning the exhaust air To heat large volumes of air with dilute pollutants to a sufficient temperature to destroy VOCs requires costly fuel and capital expenses

Need for Computer Model

There are other computer models that are related to the model developed in this research but none that performs an analysis of recirculation. One related model is EPA's HAP PRO, which is intended for permit engineers in controlling air toxics HAP-PRO does some economic analysis and outdoor air emission calculations (Steigerwald, 1996) However HAP-PRO does not address indoor air concentrations, OELs or recirculation.

The question that needs to be answered is, "what level of recirculation is safe to workers?" This can only be evaluated on a case by case basis due to differences in processes, chemicals used, application rates, building size, airflow etc It is often difficult to envision the impact that recirculation will have on a facility because a thorough evaluation of all chemical processes is needed at various levels of recirculation. Due to the significant capital costs with implementing an air control system, it is imperative that an evaluation be done beforehand to help determine the practical limits of a recirculation system. If the recirculation level is set too high, then workers may be in an unsafe environment and costly re-design and alterations may follow The computer model

developed in this study can accommodate any building size and requires information on the types of processes and products used in the facility. The model will then predict indoor air concentrations relative to OSHA and ACGIH OELs at various levels of recirculation. The model will also predict explosive/fire hazards and it will predict air control costs for VOC destruction.

This model is not intended as the final step to determine if recirculation can be implemented safely nor is it intended to be a complete evaluation concerning the use of recirculation. Rather it is intended as a tool to help in the early decision making process to gain an understanding of the issues and get an overall perspective on what level of recirculation is practical. The model is also intended to help direct air sampling by identifying chemicals with high-predicted concentrations. A more focused air sampling program can then be designed around the models outputs. It is often difficult to envision which task and which product have the greatest impact to workers' health. The computer model will not only allow the user to see the impact of recirculation on chemical concentrations but will also allow the user to see the specific task and product that creates a high chemical concentration. The model will help identify products that are good candidates for substitution. Substitution or other operational changes may be all that is needed for EPA and OSHA compliance.

CHAPTER 3
CALCULATIONS AND ASSUMPTIONS

Introduction

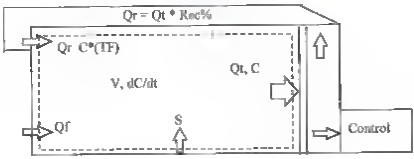
In this chapter, the main formulas used in the model to predict air concentrations are derived and the assumptions used in the model are explained. The model uses the maximum and average application rates of a product and derives a source output rate of each chemical. The products used within a particular task may each contain several chemicals. The fraction of each chemical contained in a product is used to determine how much of a chemical is being emitted. If several products used within a task have a common chemical (i.e. five different paints containing toluene), then the common chemicals from each paint are summed to arrive at the concentration during that task. In other words, the total concentration of toluene during a task depends on the partial contribution of each product in the task that contains toluene. The air concentrations used in the model are derived in the next several sections.

Air Calculations

The air concentrations are computed using mass balance equations. While there is no good substitute for proper air sampling, a predictive estimate can be obtained by

converting application rates and airflow rates into mass balance equations. The calculated results can also be used as an indicator to help guide when and where to air sample.

Figure 3-1 below is a conceptual diagram of a hypothetical building and its airflow. The dashed line represents the boundary layer that encases the air volume of interest. The total airflow (Q_t in m^3/min) is determined in the model by multiplying velocity (Vel in m/min) times the cross sectional area (Area in m^2). Q_t = Vel * Area. Total airflow (Q_t) is then split into two parts, the upper right arrow representing recirculated air (Q_r) and the lower right arrow representing exhaust air going into a control device, which is equivalent to the fresh airflow (Q_f). Q_r is computed by multiplying Q_t by the fraction of air that is recirculated (Rec%). $Q_r = Q_t$ * Rec%. The arrows on the left represent the incoming air. The lower left arrow represents the incoming fresh air (Q_f) and the upper left arrow represents the recirculated air (Q_r). The recirculated air is multiplied by TF (through filter), to signify the fact that the recirculated air will pass through a filter. The solid chemicals in a product will be filtered, which will reduce the concentration of the solids in the recirculated air proportional to the filter's efficiency. However, for liquids it will be assumed that all liquids will pass through the filter and re-enter the airstream by evaporation. V represents the volume of the facility (m^3) and dC/dt is the change in concentration (C) per change in time (t). S represents each chemical's source input rate (mg/min) computed by multiplying the usage rate of the product times the fraction of each chemical in that product (see next section for source conversions).



C – Concentration (mg/m^3)
Q_t = Total Flow Rate = Velocity * Area (m^3/min)
Q_r = Recirculated Flow Rate (m^3/min)
Q_f = Fresh Flow Rate (m^3/min)
S = Source Input Rate (mg/min)
V = Volume (m^3)
TF –Through Filter (%) = (1-Filter Efficiency)
%Rec = Fraction Recirculated

Figure 3-1 Airflow Diagram

Source Input Rate (S) Conversion

When a chemical in a product is entered as a percent, there is a choice between entering it as a percent by weight (w/w) or by volume (v/v). In most cases, a typical Material Safety Data Sheet (MSDS) is in percent by weight unless it specifies by volume. There is a slight difference in the conversion to mg/min depending on whether the chemical breakdown is entered by weight or by volume. If by weight, the product density is used in the conversion formula and if by volume, the chemical density is used in the formula. The conversions are detailed below. When computing average source versus maximum source emissions, the only difference in the conversion formulas is the maximum versus average application rates input by the user. The maximum application rate entered

by the user is used to compute maximum emission rates. The average application rate is used to compute average emission rates.

Percent by weight

If a chemical is entered as a percent by weight, which can be translated as grams of chemical/grams of product, then the following conversion is used to get the source emission rate in units of mg/min:

$$S = \frac{mg}{min} = \left(\frac{\%\ by\ wt}{100}\right) * GPH * \rho_{prod} \left(\frac{3784\ ml}{gal}\right)\left(\frac{hr}{60\ min}\right)\left(\frac{1000\ mg}{gram}\right)$$

$$S = \frac{mg}{min} = \%\ by\ wt\ * GPH\ * \rho_{prod}\ * 630\ \ 67$$

% by wt = Percent of chemical by wt (i.e. gram of chemical/gram of product)
GPH = Product Application Rate (gallons/hr) maximum or average
ρ_{prod} = Product Density (gram of product/ml of product)

Percent by volume

If the chemical is entered as a percent by volume which can be translated as gallons of chemical/gallons of product then the following conversion for mg/m^3 is used:

$$S = \frac{mg}{min} = \left(\frac{\%\ by\ vol}{100}\right) * GPH * \rho_{chem} \left(\frac{3784\ ml}{gal}\right)\left(\frac{hr}{60\ min}\right)\left(\frac{1000\ mg}{gram}\right)$$

$$S = \frac{mg}{min} = \%\ by\ vol\ * GPH * \rho_{chem}\ * 630\ \ 67$$

% by vol = Percent of chemical by volume (i.e. gallon of chemical/gallon of product)
GPH = Product Application Rate (gallons/Hr)
ρ_{chem} = Chemical Density (gram of chemical/ml of chemical.

Mass Balance Equation

$$\text{Accumulation} = \sum \text{Inputs} - \sum \text{Outputs}$$

$$V * \frac{dC}{dt} = S + Q_f * (0) + Q_r (C * TF) - Q_t * (C)$$

Get dC/dt by substituting $Q_r = Q_t * (Rec\%)$
Then, divide by V

$$\frac{dC}{dt} = \frac{S}{V} + \frac{Q_t (Rec\%)(C * TF)}{V} - \frac{Q_t * C}{V}$$

Pull out common variables $C * Q_t/V$ from the last two terms.

$$\frac{dC}{dt} = \frac{S}{V} + \frac{C * Q_t}{V} (Rec\% * TF - 1)$$

Let, $\lambda = Q_t (Rec\%)(TF-1)$

$$\frac{dC}{dt} = \frac{S}{V} + \frac{\lambda C}{V}$$

Steady State Concentration (dC/dt = 0)

$$\frac{dC}{dt} = 0 = \frac{S}{V} + \frac{\lambda C}{V}$$

$$-\frac{S}{V} = \frac{\lambda C}{V}$$

$$C(\infty) = \frac{-S}{\lambda} \text{ or } \frac{-S}{Q_t * [Rec\%(TF) - 1]}$$

This is the steady state concentration C(co) which is used to calculate the maximum concentrations for each chemical in a task. This maximum concentration is used when comparing against the STEL or ceiling limits for either OSHA or ACGIH.

Concentration at Any Time C(t)

For time weighted average calculations, one must first compute the concentration at any time or C(t). Starting with the above derivative under the Mass Balance Equation section and rearranging the formula becomes

$$\frac{dC}{dt} = \frac{S}{V} + \frac{\lambda C}{V}$$

$$\frac{dC}{dt} - \frac{\lambda}{V}\left(\frac{S}{\lambda} + C\right)$$

Let $y = \left(\frac{S}{\lambda} + C\right)$ and $\frac{dy}{dt} = \frac{dC}{dt}$

Substitute

$$\frac{dy}{dt} = \frac{y\,\lambda}{V}$$

Integrate y with respect to t (Mizrahi and Sullivan, 1982)

$$\int_{y_0}^{y} \frac{dy}{y} = \int_{t_0}^{t} \frac{\lambda}{V}\,dt$$

$$\mathrm{Ln}\left(\frac{y}{y_0}\right) = \frac{\lambda}{V}(t - t_0)$$

$$y = (y_0)\, e^{\frac{\lambda}{V}(t - t_0)}$$

Rearranging then substituting for y, Co is the initial concentration

$$\left(\frac{S}{\lambda}+C\right)=\left(\frac{S}{\lambda}+C_0\right)e^{\frac{\lambda}{V}(t-t_0)}$$

Substitute with the steady state equation on page 30

$$C(\infty)=\frac{-S}{\lambda}$$

$$-C(\infty)+C=\left[-C(\infty)+C_0\right]e^{\frac{\lambda}{V}(t-t_0)}$$

The concentration at any time (t) is

$$\boxed{C(t)=C(\infty)-\left[C(\infty)-C_0\right]e^{\frac{\lambda}{V}(t-t_0)}}$$

Time Weighted Average Concentration

It is assumed that the use of each product is at the beginning of the shift (t_0) and is used throughout the length of the product time (t_p), which is input by the user. This is a conservative assumption because the residual air concentration lingering after the product is finished being used will be allowed the maximum time for exposure. If in reality a product is used for the last hour of the shift, then the worker would not be exposed to the lingering concentrations following the use of the product. In cases where the airflow is high or the room volume is small, the lingering concentrations after the product use is negligible. The remainder of the shift length (shift length = t_d), which is also input by the user, is assumed to have no further emissions from that product. This concept is

illustrated in figure 3-2. The product is being used between time t_o and t_p. Use of the product is discontinued after t_p. The end of the work day is represented by t_d. Because of the time lag effect in concentration, there is be a gradual increase in concentration to steady state and then a gradual decrease in concentration after use of the product is discontinued at time t_p. The rate of increase or decrease in concentration is dependent on many variables to include room volume, airflow ,quantity of product being used etc. The two horizontal lines represent the average concentrations in the two regions

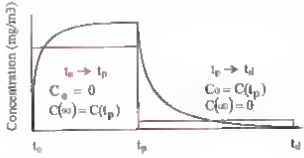


Figure 3-2 Average Concentration Over Time

To calculate the average concentration throughout the time shift, the two regions of the curve are calculated separately with their respective boundary conditions shown in figure 3-2. This formula is used for the average of a function.

$$[C_{avg}] = \frac{\int_{t_o}^{t} C(t)\, dt}{t - t_o}$$

Substitute the equation for C(t) found on page 32 and solve the integral (Mizrahi and Sullivan, 1982)

$$\left[C_{avg}\right] = \frac{\int_{t_o}^{t} C(\infty) - (C(\infty) - C_o)e^{\frac{\lambda}{V}(t\ t_o)}\,dt}{t - t_o}$$

$$\left[C_{avg}\right] = \frac{C(\infty)(t - t_o) - (C(\infty) - C_o)\frac{V}{\lambda}e^{\frac{\lambda}{V}(t)} + (C(\infty) + C_o)\frac{V}{\lambda}e^{\frac{\lambda}{V}(t_o)}}{t - t_o}$$

$$\left[C_{avg}\right] = C(\infty) - (C(\infty) - C_o)\frac{V}{\lambda(t - t_o)}\left(e^{\frac{\lambda}{V}(t)} - e^{\frac{\lambda}{V}(t_o)}\right)$$

Using this equation and substituting the boundary conditions for each region in figure 3-2, the following two expressions are derived for the average concentration in each region. For the second region ($t_p \rightarrow t_d$) slide the curve back to 0 to simplify so that $t_o = 0$ and $t = t_d - t_p$. To get C_o for the second region use the equation for C(t) on page 32 and compute the concentration at time t_p.

For $t_o \rightarrow t_p$

$C_o = 0$, $t = t_p$, $t_o = 0$

$$\left[C_{avg}\right]_{t_o\ t_p} = C(\infty) - C(\infty)\frac{V}{\lambda(t_p)}\left(e^{\frac{\lambda}{V}(t_p)} - 1\right)$$

For $t_p \rightarrow t_d$

$C_o = C(t_p)$ $C(\infty) = 0$, $t = t_d - t_p$, $t_o = 0$

$$\left[C_{avg}\right]_{t_p\ t_d} = \left(\frac{C(t_p) * V}{\lambda(t_d - t_p)}\right)\left(e^{\frac{\lambda}{V}(t_d\ t_p)} - 1\right)$$

Finally, to get the time weighted average use these expressions to average over the respective times as follows

$$TWA = \frac{(t_p)\left[C_{avg}\right]_{t_p} + (t_d - t_p)\left[C_{avg}\right]_{t_p\ t_d}}{t_d}$$

$$TWA = \frac{(t_p)\left[C(\infty) - C(\infty)\frac{V}{\lambda(t_p)}\left(e^{\frac{\lambda}{V}(t_p)} - 1\right)\right] + (t_d - t_p)\left[\frac{C(t_p) * V}{\lambda(t_d - t_p)}\left(e^{\frac{\lambda}{V}(t_d - t_p)} - 1\right)\right]}{t_d}$$

where $C(t_p) = C(\infty) - C(\infty)e^{\frac{\lambda}{V}(t_p)}$

Multiply through by (tp) and (td tp) to cancel terms and substitute for $C(t_p)$

$$TWA = \frac{\left[t_p * C(\infty) - C(\infty)\frac{V}{\lambda}\left(e^{\frac{\lambda}{V}(t_p)} - 1\right)\right] + \left[\left(C(\infty) - C(\infty)e^{\frac{\lambda}{V}(t_p)}\right)\frac{V}{\lambda}\left(e^{\frac{\lambda}{V}(t_d - t_p)} - 1\right)\right]}{t_d}$$

Divide through by t_d.

$$TWA = \frac{t_p}{t_d}C(\infty) - C(\infty)\left(\frac{V}{\lambda * t_d}\right)\left(e^{\frac{\lambda * t_p}{V}} - 1\right) + \left(C(\infty) - C(\infty)e^{\frac{\lambda * t_p}{V}}\right)\left(\frac{V}{\lambda * t_d}\right)\left(e^{\frac{\lambda}{V}(t_d - t_p)} - 1\right)$$

t_p = time product is used (min)	$C(\infty) = -S/\lambda$
t_d = shift time (min)	S = source emission rate (mg/min)
V = volume (m^3)	$\lambda = Q_t$ (Rec%)(TF-1)

This is the expression used to calculate the time weighted average of all chemicals when comparing them to OSHA PELs or ACGIH TLVs.

Vapor Pressure Maximum

The maximum concentration of a product can not exceed the vapor pressure saturation point. Therefore, if a chemical is entered into the model as a liquid and the vapor pressure concentration is exceeded then the model will default to the saturation point when comparing the maximum concentration to the ceiling or the STEL. The TWA calculations does not default to saturation, if exceeded, because even if a chemical is emitted at a rate that exceeds the saturation point, the chemical will exist as a liquid until the air clears enough to allow more evaporation. So the total mass of a liquid chemical will eventually contribute to the "average" exposure But it is appropriate to compare the ceiling level against the saturation point because the nature of the ceiling level is "never to exceed" at any time The formula for vapor saturation is given below (Caravanos, 1991)

$$VPsat = 10^6 \left(\frac{VP}{760\,mmHg}\right)\left(\frac{MW}{24.45\,lit/mole}\right)$$

VPsat = Vapor Saturation in mg/m^3
VP = Vapor Pressure of chemical (mm Hg)
760 mmHg = atmospheric pressure
MW = molecular weight (grams/mole)
24.45 Lit/mol = mole volume at 20 deg C

Lower Explosive Limit

If recirculation is set too high, it is possible to reach the lower explosive limit of a chemical mixture. When multiple chemicals are emitted, there is a cumulative effect with regards to the fire/explosive hazards. Most chemicals have a Lower Explosive Limit (LEL) around 1% (10,000 ppm) Some chemicals are lower but most are 1% or higher A rough estimation of the explosive hazard is provided in the model The model will sum up all the maximum chemical concentrations used in a task and will allow the user to change the recirculation rate and see the increasing concentrations during each task. By default all chemicals are assumed to have a 1% LEL (10,000 ppm) The NFPA-33, 1985 code that OSHA has adopted requires that the concentrations shall not exceed 25% of the LEL So as a rough estimation, 25% of 10 000 ppm or 2,500 ppm must not be exceeded Many LEL alarm systems will alert at 10% of LEL or 1,000 ppm.

There is a built in adjustment in case the user does not input a product's entire chemical make-up (100%) If there is missing information on an MSDS, a product may have less than 100% of its chemical make-up accounted for Where this occurs, a product will be adjusted to account for the missing fraction for the LEL calculations. This is to safeguard against underestimating the fire hazard by leaving out a component of a product that may contribute to the fire hazard. For example, say only 80% of a product s chemicals are loaded into the model and the sum of the maximum concentrations is 1,000 ppm. Then 1,000 ppm/0 80 = 1,250 ppm is the output reported for the LEL chart An adjustment like this is only for LEL calculations.

Bed Fires

Caution should be exercised when using a carbon adsorption concentrator. There are studies that indicate carbon adsorption systems can react with ketones and organic acids to cause hot spots in the carbon bed if the carbon is not desorbed at proper intervals or if localized concentrations build-up due to uneven airflow in the carbon bed. These hot spots can reach temperatures that can ignite the carbon bed (Akubuiro, 1993). There have been scattered reports of carbon bed fires. The Chemical Emergency Preparedness and Prevention Office of the EPA has even issued a Chemical Safety Alert on May 30, 1997 concerning carbon adsorbent bed fires (Shirley, 1997, EPA, 1997). The alert was issued due to an explosion in a carbon adsorber at a pulp and paper mill. At a Rome and Haas facility, a bed fire occurred from a solvent recovery system due to the rapid oxidation of the adsorbed organics. The facility switched to a Pedro adsorption system made by Purus Incorporated, which uses a synthetic carbonaceous material. The system is reported to have significantly reduced the risk of bed fires (Shelley, 1994). This model does not evaluate the danger of bed fires but the user must be aware of this problem and take precautions if carbon adsorption is used.

Economic Calculations

As mentioned before, the economic portion of the model uses the EPA's COST AIR model to compute air control costs. Minor modifications were made to the COST AIR spreadsheets to merge it with the model in this study. An important modification include a cost adjustment for the Regenerative Thermal Oxidizers. Recent changes due to higher demand and increased competition for RTOs, have driven prices down. This cost

adjustment is from $22/cfm of airflow to $15/cfm of airflow. The details of this modification are in chapter 6 where cost quotes from vendors are compared to the cost predictions from the model.

Another modification to the CO$T AIR model is the combining of a carbon adsorption concentrator with RTO, which was not a specifically listed technology in the CO$T AIR model. The RTO and the carbon adsorption technologies are separately listed in the CO$T AIR model. For the model in this study, the carbon adsorption system and the RTO were added together to estimate the cost. Most carbon adsorption systems will concentrate the VOCs in an airstream from 1:15. This is based on conversations with carbon adsorption vendors listed in chapter 6. The airflow to the carbon adsorber is assumed to be the fraction of air released to the control system, which is the total flow minus recirculated flow. The airflow to the RTO is assumed to be the fraction of air released to the control system divided by 15. The reduction in airflow to the RTO is because of the carbon adsorption concentrator.

Some values required by the CO$T AIR model are automatically loaded based on the input data provided by the user. For example, the BTU value of the solvents will offset some of the fuel required by the oxidizers. To estimate the BTU value of the airstream, a weighted average of each chemical that has a BTU value is estimated when the model is assembling the outputs. The formula to compute the exhaust air heat content in BTU/lb is as follows.

$$BTU/Lb_{air} = \frac{\sum_{chem}(BTU/Lb_{chem})*[Average]*10^{-6}*(ProdHrs)*(Times/Yr)}{OperHrs}$$

BTU/Lb_{air} = waste gas heat content
BTU/Lb_{chem} = input BTU/lb for chemical
[Average] = Average Concentration per task (PPM)
10^{-6} = converts ppm to fraction of airstream
ProdHrs = Length of time product is used (hrs)
Times/Yr = Number of times/year product is used
OperHrs = Annual operating hours of control device

Also the loading rate of VOCs (in lbs/hour) is automatically calculated with the user inputs. Each product's VOC content and average usage rate is used to compute the VOC output per hour, then the product with the highest output rate is used in the CO$T AIR model. The equation used to compute the VOC/hr is as follows

$$\text{Lb of VOC/hr} = \frac{\text{VOC} * \text{AvgGPH}}{454 \text{ grams/lb} * 0.264 \text{ gal/lit}}$$

VOC = VOC content of the product (gram/lit)
AvgGPH = average gallons/hr of product

Another automatically loaded value in the economic model is that the Freundlich isotherms. These isotherms are needed by the carbon adsorption technology to compute the adsorption rates of a chemical. If a chemical's Chemical Abstract Services Registry Number (CAS #) is found in the model's isotherm list, the chemical with the weakest adsorption is assumed. This assumption makes sure the model estimates enough carbon is used to avoid bed saturation. Also, the heat recovery fraction for RTO is assumed to be 95% and the heat recovery fraction for thermal incineration is assumed to be 70%. It is also assumed that natural gas is used for all three thermal controls. There are other assumptions that were made by the EPA to develop the CO$T AIR model. Details of

these assumptions can be found in the EPA COST-AIR Control Cost Manual (Vatavuk, 1989)

The cost estimates in this model are based on the cost of the VOC control device only Other costs necessary to modify the existing air handling system are not included and can be substantial. There will be costs associated with installing new ductwork, extra blowers, dampers, monitors and design work etc A rough estimate for this cost at Hill AFB is between $1 million and $2 million. However, most of these modifications are necessary to install an air control device whether recirculation is used or not It is anticipated that the cost comparisons at different recirculation levels is not substantially impacted by this omission. One should keep in mind however that the fixed costs left out of this model will increase the costs computed in this model.

Another component of cost that was not considered in this model is the cost to heat or cool the building for comfort. In cold weather recirculation will save some money in heating costs because the air being recycled has already been heated However, because the air control systems selected for this model use thermal destruction of VOCs, the return air will likely be warmer than the desired temperature when cooling is needed. The cost to heat or cool a building is generally negligible compared to the cost of the air control system and due to the variability of the inputs in computing these energy costs, heating or cooling costs will not be addressed in this study The climate control of the building should however be considered when deciding on recirculation.

General Assumptions

1 Even mixing – The air within the facility is assumed to be evenly and rapidly mixed throughout the building

2 Constant source output rate – The source output of each chemical from the products is held constant at the application rate input by the user

3 Accurate MSDSs – The material safety data sheets (MSDSs) are accurate and complete Note Restricted versions of MSDSs, which are provided to health professionals were used in the case study because they contain better detail on the chemical makeup of each product Unrestricted MSDSs, which are designed to protect company trade secrets, can be used in the model but the restricted MSDSs provide more detail on the chemical makeup of a product

4 Overspray – The amount of overspray is the quantity of product that does not stick to the aircraft and will become airborne The solvents are assumed to evaporate 100% but the solids in the paint will be affected by the overspray which is input by the user If 50% of the product is overspray then 50% of the solid components and 100% of liquids components will contribute to indoor air concentrations (see How Applied on page 60 for more detail).

5 Constant filter efficiencies – New filters will generally become more efficient over time as they "cake" with solid particles In the case study of C-130 painting the filters are replaced after three aircraft have been painted As a conservative assumption, the lowest tested removal efficiency for clean filters will be assumed in the model.

6 Ignore tasks that do not consume products – This model uses mass balance calculations to determine indoor air concentrations. These calculations require application rates to determine concentrations. If a task does not consume a chemical product the task can not be evaluated in this model and a source emission rate can only be determined through proper air sampling. One such task, Scuff Sanding a painted aircraft will be ignored in this demonstration even though it can produce hazardous emissions.

7 Instantaneous evaporation – The application rate of the product will be used to determine the source emission rate. In other words, if it takes one hour to apply one gallon of Toluene, then one gallon/hour is the evaporation rate. But it may actually take three hours for toluene to fully evaporate would yield an evaporation rate of 0.33 gallons/hour. This is a conservative assumption because chemicals will evaporate more slowly than the application rate. The maximum concentration will therefore be higher with a faster evaporation rate versus a slower evaporation rate. Other evaporation models exist (Kunkel, 1991: 19) but due to the complexity of determining actual evaporation rates, the application rate of the product is substituted in this model.

8 Synergistic effects ignored – The synergistic effects of multiple chemicals are ignored. In the model, each chemical is measured against its OEL separately. Some chemicals can have a synergistic effect with each other. OSHA uses a formula to compute a new OEL for chemicals that have a similar target organ (i.e. both effect the liver). This type of analysis is not done in this model.

9 No personal protective equipment (PPE) used – The model ignores PPE such as respiratory protection. However the user can easily determine if respirators will be protective by comparing the highest relative concentrations to the assigned protection factor (APF) of the type of respirators used If the highest concentration is 15 times the exposure limit and the type of respirators used have a APF of 25, then the worker would be protected.

10 User estimate on rinsing – Some products are applied then rinsed off which will eliminate evaporation of solvents to the facility as long as the fluid exits the building In this case, it would be incorrect to assume the entire product evaporates in the building, so the user may adjust the quantity of product left over to evaporate by inputting the fraction that is rinsed away There is no easy way to determine the quantity lost unless either the rinsate or the air is sampled. Therefore, the users best estimate is assumed to be accurate for the purpose of this model. If the product is rinsed, but rinsate is allowed to sit in the facility to evaporate, then no rinsing should be input because the product would still be allowed to evaporate in the facility

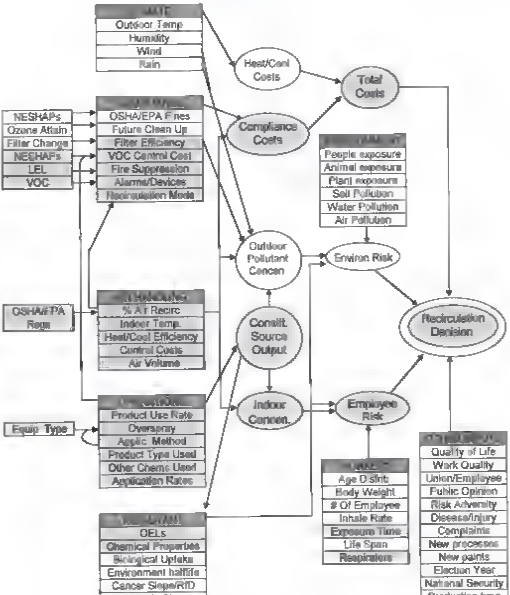
11 Economic model based on EPA's control cost estimator – The EPA has assembled a cost model for various technologies known to reduce VOCs. The models have been altered to work in this model but all formulas were left intact and are assumed to be accurate

12. Fuel for air control device is assumed to be natural gas.

13 Fresh air intake is clean – It is assumed that the fresh air intake is uncontaminated with pollutants

14 Adequate fire protection – Fire hazard is a significant concern with recirculation. While the model addresses the fire issue to some degree, it will be assumed that adequate fire safety systems including LEL alarms and sprinkler systems have been installed and are inspected routinely

15 Other issues like political, ecological or quality of life issues that may significantly influence the decision to recirculate will be ignored for the purpose of this study Issues such as nuisance odors, future litigation, future clean-up costs, EPA or OSHA fines may have an additional impact beyond the scope of this work. A decision making diagram describing some other issues that will influence the decision to recirculate can be found in figure 3-3 This model will address some of the issues, others are qualitative and should be considered when deciding on whether recirculation can be implemented



Shaded variables are considered in this study, others are ignored

Figure 3-3 Input Diagram for Recirculating Decision

CHAPTER 4
USER'S MANUAL FOR RECIRCULATION MODEL

Introduction

This chapter is intended as a user s manual for the recirculation model. If this document is being viewed on an electronic format, use the "find" feature of the program to look for a key word. Also, if this document was launched from the help button in the recirculation model, select Excel on the Microsoft Start Bar to get back to the model from this Word document.

The model is designed to predict maximum and average indoor air concentrations relative to OSHA or ACGIH OELs. It is designed for use by an industrial hygienist or environmental engineer contemplating the use of recirculating industrial air in a building as a means of reducing air control costs. The model takes information about hazardous products used in a building and how they are used to assess whether indoor air concentrations will build-up to unacceptable levels at various amounts of recirculated air This model is not intended to give a yes or no answer regarding recirculation, nor is it intended as a substitute for proper air sampling. It is intended as a tool to understand the decision and optimize the level of recirculation to cut environmental emission control costs while keeping workers safe from chemical exposure It can also be used as a screening tool for air sampling to determine which task, product and chemical has the greatest

impact to workers' health. The model can help guide air sampling methodology and timing.

The model calculates chemical concentrations using mass balance equations (see Chapter 3). An interactive chemical database with over 1300 chemicals works in conjunction with the model. Chemicals can be searched by CAS # or by chemical name. The database includes OSHA PELs, STELs, ceiling limits and equivalent ACGIH limits (as of June 1997). The database also includes molecular weight, specific gravity, vapor pressure and other chemical specific types of information. This database was assembled to reduce the amount of information required from the user. The database was assembled using information from the sources listed below:

- 29 CFR 1910.1000 – Table Z-1, Limits for Air Contaminants (OSHA, 1997c),
- 29 CFR 1910.1000 – Table Z-2, Toxic and Hazardous Substances (OSHA, 1997d),
- 29 CFR 1910.1000 – Table Z-3, Mineral Dusts (OSHA, 1997c),
- Commercial chemical databases on the internet (CambridgeSoft, Vermont Safety and Information Resources)
- 1997 ACGIH Threshold Limit Values Limit Values® Booklet (ACGIH, 1996),
- CHEMINFO – chemical database on CDROM from Canadian Occupational Health and Safety Office,
- NIOSH Pocket Guide to Chemical Hazards (NIOSH 1990),
- Handbook of Chemistry and Physics (75th Edition) (Lide, 1995),
- Chemical Principles (5th Edition) (Masterton et al 1981) and
- Database from Air Force Bioenvironmental Engineering software called BEEKEEPER[2] (Moreno)

The required inputs to the Excel spreadsheets are entered by the user through Visual Basic for Applications (VBA). The VBA input forms are installed automatically when the Excel file is opened. Always go through the VBA input forms to modify data in

[2] A chemical database from Air Force software for industrial hygiene surveys

Excel because several problems can arise by trying to add data directly to Excel. If the VBA input forms are closed, the model returns the user to the Excel spreadsheets. To reload the VBA input forms, click the button on the top of nearly every spreadsheet labeled "Back to Visual Basic Inputs > " This will reload the VBA input forms. Some spreadsheets in the model are automatically protected when the VBA forms are closed. Each spreadsheet in Excel and a brief description of each is listed below:

Excel Graphs Created By Running Model

- 10Yr Cum Cost – Cumulative cost over 10 years at one recirculation level,
- Rec Vs. Cost – Graph of annualized cost at various recirculation levels,
- TWA_PEL Chart – Highest chemical's TWA/(TLV or PEL) per task,
- Max Chart – Graph of highest chemical's Max/(STEL or Ceiling) per task,
- VOC Lb_Yr – Graph of annual pounds of VOC output by task,
- TaskHrs_Yr – Graph of annual working hours per task,
- LEL – Graph of Lower Explosive Limit relative to recirculation level per task,

Outputs Created By Running Model

- MAX – Computes maximum concentrations for each chemical by product (mg/m^3),
- Max%STEL – Maximum concentration per STEL or ceiling (ratio),
- AVG – Computes average concentrations for each chemical by product (mg/m^3),
- TWA%OEL – Average concentration per PEL or TLV (ratio),
- Date – Sums Max/STEL and TWA/OEL for each chemical within a task,
- Charts – Highest Max/STEL and TWA/OEL per task while recirculation is varied,
- Top 4 Chem – Returns the four chemicals with the highest relative concentrations in the selected task,

Input Storage Sheets

- Gen Inputs – General information about the building size, airflow etc.,
- Control Costs – Stores utility inputs and computes air control costs,
- Chem Inputs – Main sheet, stores all task, product and chemical information,
- Lists – Stores chemical database and other information.

The above four Input Storage Sheets are protected whenever the user exits the VBA input forms and goes into Excel so that accidental entries are not made. All other spreadsheets

and graphs, use the raw data in these four sheets. Many of the cells in the above four spreadsheets have named entries that the model uses and can not be altered or the model will fail to run.

WARNING The working end of the model is really the Excel spreadsheets but due to the complexity of the sheets, the VBA input forms are used as a means of loading the data and viewing the outputs. At anytime, the user is allowed to go to Excel directly however the macros, which assemble the customized spreadsheets and graphs, will not run if information is not installed correctly The information is loaded more easily and properly through the VBA input forms. Also, the VBA input forms contain an error checking system so the model gives a warning if for example, a number is required and a letter is input. If the user enters Excel directly, the most important sheets will be protected but do not to alter the locations or the names of the cells in the input storage spreadsheets. Changing some parameters in the graphs (i e bar charts to pie charts) or copying data to another Excel file is permissible. Always make a back up copy of the model in case something is inadvertently altered causing the model not run to properly

The rest of this chapter is organized by VBA input forms in the order that they appear to the user when using the recirculation model.

Task-Product-Chemical Form (Main Form)

The form shown in figure 4-1 is the main VBA input form and every other form can be loaded from this one Most of the time spent inputting data will be from this form because all the tasks, products and chemicals are loaded into this form. On the top of this

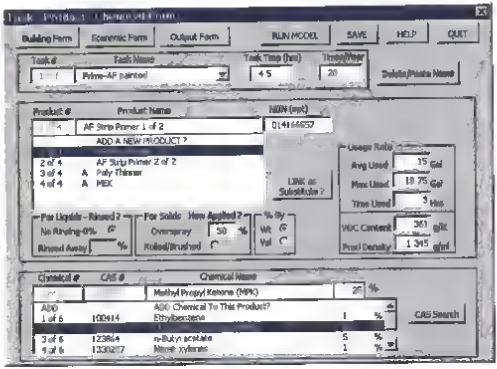


Figure 4-1 Task-Product Chemical Form Window

form, there are several control buttons and below these buttons are three large frames (unless no tasks are loaded then only the upper form is shown)

- Upper frame – to input tasks,
- Middle frame – to input products used in the task shown in the upper frame and
- Lower frame – to input chemicals as a percentage of the selected product

Buttons On Top

- Building Form – Loads the Building Form, for building dimensions etc
- Economic Form – Loads the Economic Form, for utilities costs etc

- Output Form – Loads the Output Form. Use of this button should be limited because the output data are created when RUN MODEL is pressed and the Output Form will automatically appear afterwards. The RUN MODEL selection is the most efficient way to get to the Output Form because the data will be up-to-date with a new run. Whenever the VBA input forms are loaded such as when the file is initially opened, the output sheets are automatically cleared to make data entry faster
- RUN MODEL – When finished loading all data, hit this button to start the macros in assembling the output formulas and graphs in the spreadsheets. The first thing that will happen is the form shown in figure 4.2 will pop-up. Select between using OSHA exposure limits only or OSHA and ACGIH limits (the most stringent limit is applied if both are selected). To make a different selection, the RUN MODEL button must be selected again to reassemble the graphs. Once the selection is made, press continue and let the model run completely. Do not try to stop the Excel macro while it is running or the file may be damaged. The macro takes several seconds to run (40 seconds on a Pentium 200 with over 60 products loaded). The macro assembles the customized graphs and formulas relative to the input data that have been entered into the spreadsheets. The model must be run each time information is changed or each time the VBA input forms are re-entered (output spreadsheets are cleared when VBA input forms are loaded to increase the speed during data entry). If the model is not run after a change is made, the charts will show old information or no information at all.
- SAVE – Saves all input data. This is the same as being in Excel and selecting "Save As." It is highly recommended that this button is always used to save the model.

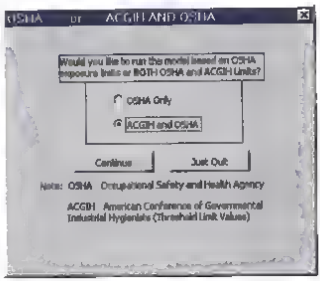

OSHA or ACGIH AND OSHA
Would you like to run the model based on OSHA exposure limits or BOTH OSHA and ACGIH Limits?
OSHA Only
ACGIH and OSHA
Continue
Just Quit
Note: OSHA Occupational Safety and Health Agency
ACGIH American Conference of Governmental Industrial Hygienists (Threshold Limit Values)

Figure 4-2 OSHA or ACGIH and OSHA Selection

When the user gets out of VBA input forms and tries to close Excel, Excel will usually remind the user to save the work. Do not save the file from Excel because there is a chance that all the output data is still in the spreadsheets and the file will be much larger. Then, the next time the model is used, it will run much more slowly. It will still be slow even if the user clears the sheets by re-entering the VBA input forms. To correct an accidental save from Excel, simply open the VBA input forms which clears the output sheets, save the model from the VBA main form then close and re-open the model (remembering not to save when the Excel prompt appears). It is best to remember to save the work from the VBA inputs sheets because the outputs spreadsheets are always cleared when the model has the VBA input forms loaded.

- HELP – Opens this help document as long as this document is named "Readme.doc" and is loaded in the same sub-directory as the Excel model

- QUIT – To quit after the work has been saved from the SAVE button in the VBA main form, click the QUIT button to get out of VBA input forms and into Excel. Then close Excel as normal but do not save the file when the Excel prompts appears. Save the work from the VBA main form only to ensure output spreadsheets are cleared.

Delete/Paste Pop-Up Menu

The pop-up menu shown in figure 4 3 will appear if the button labeled "Delete/Paste Menu" is clicked or the right mouse button is clicked in an area outside the three frames The pop-up menu will disappear if the QUIT selection is made in the pop-up menu. The pop-up menu has the following selections

Figure 4-3 Delete/Paste Pop-Up Menu

- Copy Product – This selection copies the selected product row in Excel and all its chemical inputs.
- Paste Product – This selection pastes a copied product to another task. Copy Product must be selected first and then a new task must be highlighted before Paste Product can be selected. If something else is performed between copy and paste the row selected in Excel may be lost and an error may occur If a product is pasted, all

product and chemical data are pasted into the selected task including usage rates, how it is used etc Check this information if this pasted product is used differently in the new task. The advantage of pasting is to avoid having to re-enter the chemicals and the product name etc

- Delete Task – Deletes the selected task from the model and all products associated with the task. A warning will appear indicating which task is about to be deleted There is no "undo" function after a task is deleted The "Delete Chemicals In Model" form shown in figure 4-4 will appear if this selection is made and it will list all chemicals in the model not attached to a product. See the "Delete Chemicals in Model" form below for a further explanation.
- Delete Product – Deletes the selected product from the model. A warning will appear indicating which product is about to deleted. There is no "undo" function. The "Delete Chemicals In Model" form shown in figure 4-4 will appear if this selection is made and it will list all chemicals in the model not attached to a product See the "Delete Chemicals in Model" form below for a further explanation.
- Delete Chemical – This selection deletes an individual chemical from the model (not the database) Because the entire chemical column is deleted in Excel, if the chemical selected for deletion is used by another product a warning will appear indicating that another product is also using the chemical. The user can then quit or continue to delete There is no "undo" button. If the user wants to delete a chemical from only the selected product, just delete the number next to the "%" on the main form while the product is selected The chemical will be deleted as a constituent of that product but the entire chemical will not be deleted from the model

- Delete All – If the user wants to start fresh, this selection will clear all tasks and associated products. The "Delete Chemicals In Model" form shown in figure 4-4 will appear if this selection is made and it will list all chemicals in the model not attached to a product. See the "Delete Chemicals In Model" form below for further explanation.
- QUIT – Closes the pop-up menu. Also, the left mouse button clicked in the area outside the three main frames will also make the pop-up menu disappear.
- Delete Chemicals in Model Form – If either "Delete Task", "Delete Product" or "Delete All" is selected, the chemicals that do not have any products associated with them will be displayed as shown in figure 4-4. It is presumed that only these selections

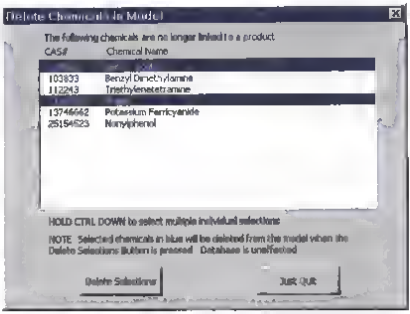


Figure 4-4 Delete Chemicals in Model Form

will create unattached chemicals so this window will only appear if one of these three selections is made. The user may select any one or all of these chemicals to delete, however due to software limitations only 50 chemicals can be deleted at a time. Only the

selected chemicals highlighted in blue will be deleted from the model. If all chemicals are associated with at least one product, this form will not appear after a deletion. The chemicals in the chemical database are never deleted but can be revised (see Chemical Input Form below)

Task Frame

The upper frame is for tasks. The user should first flowchart the process with inputs from the shop supervisor to understand the types of operations and tasks involved in the building under evaluation. This is a standard part of an industrial hygiene survey. A separate task should be established whenever an operation involves a difference in the type of products being used or a significant difference in the application rate of the products (see Chapter 5 for methods to determine tasks, products etc.). However, it is permissible to add several products within the same task that are substitutes for each other. For example, if either MEK or Toluene is used during a cleaning task, then they can both be added to the cleaning task and linked as substitutes (substitute links are explained in the Substitute section below). Each task is handled as a separate chemical emission entity. For example, if 10 products each containing some amount of toluene are used in a task, the toluene from each product is summed to compute the indoor air concentrations of toluene for that task. The inputs in the Task Frame (upper frame) are as follows

- TASK # – No input is needed. Tasks are automatically counted.
- Task Name – The task name can be any name the user wishes to uniquely identify a task. To change the name in the task box, type the new name in the box and hit enter. The "Add Task?" box shown in figure 4.5 will then pop-up to ask if the user wants to add a new task or just rename the existing task. The first item in the task drop down

box labeled "ADD A NEW TASK?" will also set the form to add a new task. The product and chemical frames will be hidden until all information is added in the task frame

Figure 4-5 Add Task Box

- Task Time (hr) – Enter how many hours on average the task takes to perform. This is for a time per task chart, which illustrates the annual time spent per task.
- Times/Year – Enter how many times per year the task is performed.

Product Frame

Each product involving hazardous chemicals is added to the selected task from the product frame. The Material Safety Data Sheet (MSDS) on each product is necessary for the product frame add the chemical frame. If a 2-part product is entered, each product must be entered separately and the corresponding quantities adjusted for their mixing ratios. For example, if 10 gallons of a 2-part paint is used with a mixing ratio of 1.4, then enter part one as a separate product with two gallons used and part two as a separate product with eight gallons used.

- Product # – No input is needed. This box automatically displays the number of products
- Product name – Enter a unique name for each product (i.e. Red Poly Paint)

- NIIN – The National Item Identification Number (NIIN) is an optional input to help identify and track a product based on its NIIN (located on the MSDS) All or part of the NIIN can be entered here.
- Product List Box – This box displays a list of the products that belong to the task selected in the task frame above Click on a product in this box to display all corresponding information about that product along with the chemical breakdown of the product (in chemical frame below) When a product is selected, any attribute in the product frame can be changed and the "Update/Add Product" Button will appear This button must be clicked to update or add to the model. The top entry in this listbox is always "ADD A NEW PRODUCT? " Clicking this entry allows the user to add a product to the selected task To delete, copy or paste a product hit "Delete/Paste Menu" button (see pop-up menu above) Products are listed in the order they are entered. Also, an alphanumeric (A, B, C etc) will appear before two products that are linked as substitutes for each other Substitutes need to be entered next to each other to link them (see substitute links below)
- Rinsed – This rinsed section will impact only the liquid fraction of a product. If the product is applied and left to evaporate then choose "No Rinsing – 0%." If the product is applied then rinsed off to exit the building (rather than left as a puddle to evaporate), enter an estimate of the percentage of product that is rinsed away Keep in mind that the rinsed away fraction will be directly multiplied to the air concentration of a liquid chemical. Therefore, if 95% is rinsed away and the air concentration for a particular liquid chemical in this product would otherwise be 100 mg/in^3, then the air

concentration will be 5 mg/m^3 representing the fraction that is left to evaporate. Only liquid fractions of the product are handled in this way as shown in table 4-1 below.

Table 4-1 Rinsing Effect on Solids and Liquids.

Rinsed Away ?	Solids Airborne/Total	Liquids Airborne/Total
No Rinse	Overspray %	100%
95%	Overspray %	5%

- How Applied – The how applied section impacts only the solid chemicals (i.e. metals) of a selected product. If a product is sprayed on, then the solid fraction of the product that becomes airborne is determined by the amount of overspray. If the product is rolled or brushed on, it is assumed that the solid chemicals of the product will not become airborne. The liquid chemicals of the product is unaffected by how it is applied. Liquid chemicals are assumed to evaporate 100% over the time that the product is being used because the liquid chemicals will evaporate regardless of overspray.

  Several studies have assessed the amount of overspray with various types of spray nozzles and products. In one study, various paint spray nozzles were assessed at 10-30% overspray by weighing the painted part before and after. However that was under laboratory conditions, actual overspray ranges are closer to 40-60% depending on technique, applicator and a variety of other factors (Carlton and Flynn, 1997 557). The type of spray equipment used will have a big effect on overspray. Table 4-2 summarizes data gathered on paint spray systems (Ayer and Hyde, 1990).

Table 4-2 Paint Spray Gun Transfer Efficiency

Paint Spray Gun Type	Transfer Efficiency	Overspray
Electrostatic Spray Systems	60-90%	10-40%
Air Assisted Airless Systems	12-72%	28-88%
Air Atomized Systems	12-68%	32-88%

If large droplets are being formed (i.e. garden hose), then less overspray should be used such as 5-10%. There is a direct 1-1 relationship with indoor concentrations of solids and overspray. For example, if 40% overspray is entered, then the air concentration will be computed using 40% of the mass of the solid chemicals in that product. The table below (table 4-3) shows the effect of overspray as they relate to the airborne concentrations of solids and liquids in a product.

Table 4-3 Overspray Effect on Solids and Liquids

Overspray	Solids Airborne/Total	Liquids Airborne/Total
40%	40%	100%
Rolled or Brushed (0%)	0%	100%

- % By Wt or Vol – Select whether the chemical makeup of the product is entered by weight or by volume on the MSDS. Typically, chemical percentages are by weight unless otherwise specified on the MSDS.
- LINK As Substitute – There are often cases when product substitutions occur. For example, different products may be used in the same task under different conditions (hot versus cold weather). When either one product or another is used in a task to do the same thing, the products can be considered substitutes even if usage rates vary. The "LINK As Substitutes?" button is a toggle switch that will link (or unlink if they

are already linked) the currently selected product with the product immediately below it. Substitute products must be entered next to each other to be linked. If there is only one product or the last product is selected, the "LINK As Substitute" button will disappear. When the products are not linked and this button is clicked, the products will be linked. An alphanumeric placeholder will appear in the product list box just before the product name. At times "B, B" may appear when there is no "A, A." This is normal and the products will still be treated as substitutes. To link more than two products, select the lower of two linked products shown in the list box and click the "Link as Substitute?" button. All three products will now be linked. The model will handle linked products by checking each chemical and the one that has the largest concentration relative to its respective OSHA or ACGIH limit is added to the chemical emission for that task. This is done on a chemical by chemical basis so it is possible for different substitute products to be added under different chemicals.

- Avg Used – This is used to determine the Time Weighted Average (TWA) air concentrations. Enter how many gallons of this product is used on average within the task.
- Max Used – This is used to determine whether a ceiling or STEL limit may be exceeded. Enter the maximum number of gallons used within the task. If left blank, the average will be used.
- Time Used – This is the length of time a product is used within a task. Product time used may not exceed the Task Time. If this occurs a warning will be given. "Time Used" is important to the time weighted average (TWA) exposure calculations. If a product time used is two hours during an 8-hour shift and the concentration is 10

mg/m^3 in the two hours, then a TWA of 2 5 mg/m^3 ((10 mg/m^3 * 2 hrs + 0 mg/m^3 * 6 hrs)/8 hrs) is expected.

- VOC Content – Enter the Volatile Organic Compounds (VOC) content of the product in grams/liter This is to help determine how much VOCs are being emitted by the facility per year and the model will break VOC emissions down by task It also is used in determining the control costs. Often the VOC content can be found on an MSDS as a chemical ingredient entry in grams/liter If VOC content is not given, it can be computed with the percent volatile on the MSDS, as long as there is no water in the product. Multiply the percent volatile by the product density and convert to grams/ml.
- Prod Density – Enter the density of the product found on the MSDS in grams/ml. If the product density is not given, divide the product weight (lbs) by the product volume (gal) and convert to grams/ml if needed A value of 1 0 gram/liter is assumed if density is left blank
- ADD PRODUCT Button – This yellow button is visible only when "ADD A NEW PRODUCT" is selected or if one of the product's attributes is changed. To add or change a product, this button must be pressed after all product information is entered. All information is checked at this point for proper entry

Chemical Frame

- Chemical # – no input needed, automatically counts chemicals
- CAS # – The small box labeled CAS # is disabled until the first entry in the chemical list box labeled "ADD CHEMICAL TO THIS PRODUCT" (sometimes just the word "ADD" appears) is selected. Enter the full CAS number (no dashes) of the chemical to

be added and hit return. The CAS # can be found on the MSDS and it is used to uniquely identify a chemical. If the CAS number is recognized as previously input in the model or if the CAS # is found in the chemical database, the Chemical Data form will automatically open with all the information loaded about that chemical. From the Chemical Data form the data can be inspected and modified. In the upper left box labeled "percent," enter the percent of the chemical found in the product. Then press the ADD CHEMICAL button and the information will be loaded into the model (for more information on the Chemical Form, see below). The form will then disappear and the chemical will appear in the chemical list box for the chosen product. If the CAS # is not recognized, the model will ask if the user wishes to input a new chemical manually. If yes is selected, the chemical input form will appear with only the CAS # and product name loaded. Enter the chemical information here and press ADD CHEMICAL. The entries are screened for proper entry and the model will ask if the user wants to add the new chemical to the database also. A chemical can be deleted from the model but it can not be deleted from the chemical database. The information in the database can be altered but a CAS# can not be deleted from the database.

- Chemical Name – The chemical name can be changed at anytime and the model will be updated. However, the next time that chemical is entered into a product, the model will detect that the name in the model is be different than the name in the chemical database and the model will ask if the user wishes to update the database. The names in the database are generally International Union of Pure And Applied Chemistry names (IUPAC) with abbreviations or common names in parentheses to assist when searching.

- Percent (%) – The percentage of a chemical in the selected product can be changed from this box. If the number is deleted and a blank is left, the chemical disappears from the selected product (to delete the chemical entirely from the model, select delete chemical from the pop-up menu, see above) On the MSDS, a chemical may be given with a percent range or "unknown" for the percentage In the case study to follow, a percent given as a range was averaged (i.e. 20 – 50% was entered as 35%). Unknowns or blanks were left out of the case study In many cases, chemicals on an MSDS that are not given a percentage are not highly hazardous substances and do not have an OEL. There are different versions of MSDSs. Medical professionals can get the restricted MSDS versions where more of the chemical information is given The unrestricted version may have less information due to proprietary concerns.
- CAS Search Button – This button will pop-up a search form that allows the user to search a chemical by name or by part of a name When the search form pops up enter any part of a chemical name and it will search and display matches. To see a complete list of chemicals in the database hit the "View All" button (see Chemical Search Form below for more details)
- Chemical List Box – This box will display the CAS #, chemical name and percent (%) of all chemicals loaded for the selected product. It is updated each time a new product is selected. Double Click on any chemical and the Chemical Data Form pops up automatically with all information loaded in the model. This information is loaded from the model and can be different from the database if a change was made to the model without updating the database

Chemical Data Form

To get to the Chemical Data Form shown in figure 4-6

a. double click on a chemical in the chemical list box at the bottom of the Task-Product-Chemical Form

b. enter a new CAS # that is found in the chemical database If not found, this form will still appear but it will be blank so a chemical can be added

c select "CAS Search" and double click on a chemical in the search form.

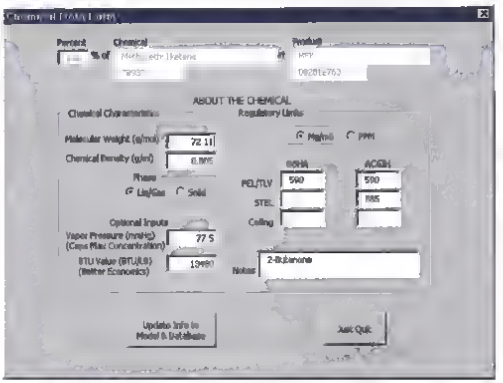


Figure 4-6 Chemical Data Form

In all cases, the chemical is added to a product or information about the chemical can be updated using the "ADD Chemical" Button at the bottom.

- Percent (%) – If an existing chemical was double clicked to get to the Chemical Data form (method a. above), the percent is displayed but the percent can not be altered. To alter a chemical percent for a chemical already loaded into the model, change the percent from the main form. If the chemical form appeared by methods (b) or (c) above the percent box will be blank and the percent can be entered at this point. A percent must be input or a warning will appear when the "Add Chemical" Button is selected
- Chemical – The chemical name and CAS # are displayed but they can not be altered from this form. The chemical name can be altered in the main form (see above)
- Product – The product name and NIIN can not be altered from this form but they are displayed to remind the user which product the new chemical is going to be added. The product name and NIIN can be altered in their respective boxes on the main form (see above)

Chemical Characteristics

- Molecular Weight – Enter or check the molecular weight of the chemical (grams/mole)
- Chemical Density – Enter or check the chemical density (Sg) of the chemical (grams/ml). Note: Do not confuse this with the product density
- Phase – Enter or check whether the chemical exists as a solid or liquid at room temperature. If the chemical is a gas, enter it as a liquid. The model handles a gas and a liquid in the same way. Phase is important in determining how filtration and overspray will effect the chemical (see overspray and how the chemical is used above). If there is no entry for phase, the model will assume the chemical is a liquid

This is more conservative because a liquid is assumed to pass through a filter and completely evaporate

- Vapor Pressure – Enter or check the vapor pressure in mmHg. The vapor pressure is used as the maximum concentration of a liquid if the steady state concentration exceeds the vapor pressure concentration of the chemical. The air concentration of a liquid can not exceed its partial pressure in air (see Chapter 3 for vapor pressure calculations)
- BTU Value – The British Thermal Unit Value (BTU Value) in BTU/lb of chemical is an optional input but will make the economic section more accurate. The average of all chemical contributions to the BTU value is added to the EPA Cost Estimator Model. The contribution of heating value from the pollutants is subtracted from the auxiliary fuel required to heat the air to a temperature needed to destroy VOCs. If there is a significant contribution of BTU value from chemicals, then less fuel is needed to heat the air

Regulatory Limits

The units for the regulatory limits can be toggled between parts per million (ppm) and mg/m^3. The model always uses mg/m^3 but even if ppm were selected, the model automatically switches to mg/m^3 when loading the values into the spreadsheets. Acronyms that will be used in the model are listed below. For a more detailed explanation of these and other acronyms, see the glossary section.

PEL – Permissible Exposure Limit
TWA – Time Weighted Average
OEL – Occupational Exposure Limits
STEL – Short Term Exposure Limit
Ceilmg – maximum concentration allowed at any point

Conservative industrial hygiene practices and local policies may require using both ACGIH limits and OSHA limits (whichever is lower) but only OSHAs limits are legally enforceable. When "RUN MODEL" is selected, the model will give a choice of running the model using OSHA limits only or the most stringent of both OSHA and ACGIH limits. The model must be run each time if the user wishes to change this selection. All STELs and Ceilings are treated the same in the model. The difference between Ceilings and STELs is subtle (STEL allows exposure for up to four times/day for 15 minutes at least one hour apart, ceiling limits are never to exceed). The maximum concentration is divided by either the ceiling or the STEL to determine if a maximum threshold is exceeded for a given chemical. The TWA is divided by the PEL to determine if the average threshold is exceeded.

The regulatory limits in the chemical database were assembled from a variety of sources (see Introduction to this chapter). Some compounds such as chromates, lead, tin, aluminum, cyanides etc. are reported by OSHA or ACGIH using general limits. These general limits apply to any chemical that contains the given compound and the limit should be adjusted to account for the molecular weight of the chemical. In these cases, several common chemicals containing each chemical structure were added to the database and the limits have already been adjusted to account for the differences in molecular weight.

Often these general limits and some specific chemicals are listed with descriptors such as "as Cr" or "as Hg." For example, chromates have an OSHA ceiling limit of 0.1 mg/m^3 "as CrO_3" (MW of CrO_3=100). So when adjusting for the compound strontium

chromate (MW of CrO_4Sr =203 6), the ceiling limit for strontium chromate becomes 0 1 mg/m^3 * (203 6/100) = 0 2036 mg/m^3

Also, the ACGIH TLV listed for strontium chromate is 0 0005 mg/m^3 "as Cr" (MW of Cr= 52) so the ACGIH TLV for strontium chromate (MW of CrO_4Sr = 203 6) becomes 0 0005 mg/m^3* (203 6/52)= 0 00196 mg/m^3

Therefore some chemicals will be loaded in the database even though they are not specifically listed in OSHA or ACGIH lists OSHA and ACGIH limits should be checked routinely as they change from year to year The database is updated to the 1996 ACGIH TLV booklet for ACGIH Limits and up to June 1997 for OSHA Limits. In addition, some chemicals have a separate Code of Federal Regulation (CFR 29 1910 series) with OSHA limits listed in them. All known regulations were consulted to determine the limits of these separate chemicals and the CFR that refers to that chemical is given in the "Notes" entry of the Chemical Input Form when the chemical is loaded

- Notes – A general note block is provided for any use such as an explanation of limit adjustments, a chemical synonym name or the name of a unique regulation that governs the chemical. In some cases a note will appear with the word "as" followed by a chemical symbol such as "as F " This means the limits for that compound were adjusted for the molecular weight of its fluorine content (see regulatory limits above for calculations) Several metal containing compounds that are not specifically listed in the OSHA or ACGIH chemical lists will have will have this type of message in the note block

- "Add Chemical To Product" Button – When all chemical data has been entered or loaded, click this button to add the chemical to the product. The data entered will be checked for errors and added to the model. If an error is found, a warning message will appear and the error will be highlighted. When looking for a CAS number, the model automatically looks for the model's information first, then the database is checked. When the user attempts to add the chemical to a product, if the CAS# is found in both the model and the database, the information is screened to be sure the model and the database agree. If there is a difference in any part of the chemical information, a special form will appear to show the difference and allow the user to update the database. If the database and the model agree, this special form will not appear.
- Just Quit – goes back to the Task-Product-Chemical Form with no changes.

Chemical Search Form

Press the CAS Search button in the Task-Product-Chemical Form of the main form to get the Chemical Search Form shown in figure 4-7. If only a chemical name or part of a name is known, use this search form to locate a chemical in the database. When the form pops up, enter any part of a chemical name and the model will search and display all chemicals that matched the search phrase. Use the "View All" button to see a complete list of chemicals in the database. A star (*) before the name indicates that the specific gravity (Sg) and molecular weight (MW) of the chemical are available. MW is required for the model to run and Sg is preferred. Select a chemical by double clicking on the chemical. The Chemical Search Form will disappear and the Chemical Data Form will

automatically appear with all loaded information about that chemical. At this point, enter a percent and press "Add Chemical" to add it to the selected product.

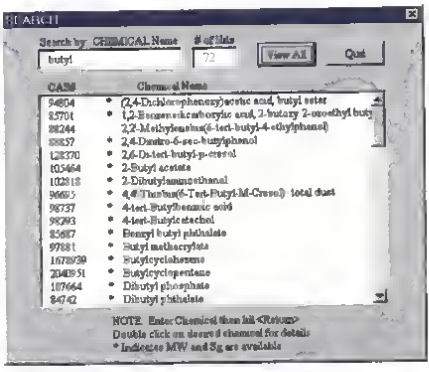


Figure 4-7 Chemical Search Form

Building Inputs Form

The building input form shown in figure 4-8 will appear when the button labeled building form is clicked in the main form.

- Units – This selection toggles between Standard International (SI) units and English units. The model always adds the data to Excel in SI units but the data can be viewed or input in English if this is preferred.

- Building Dimensions – Input the appropriate height, width and length of the building or booth being considered for recirculation.

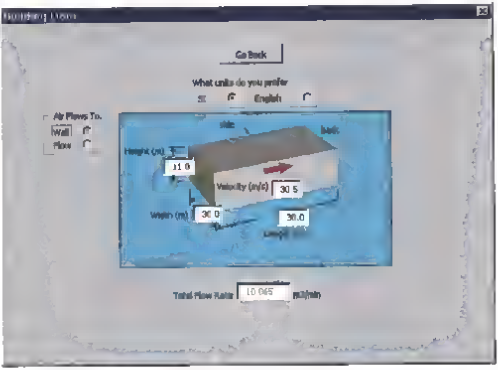


Figure 4-8 Building Input Form

- Velocity (m/s) – Input the velocity of the airflow in the building in ft/min or m/sec At an Air Force Base the Bioenvironmental Engineering Office can be consulted for this. There are regulations for many workplaces requiring a certain airflow for a particular type of workplace
- Airflow – In most cases, the airflow direction is horizontal (towards a wall) but some buildings are designed so that the airflow is vertical (toward the floor) The airflow direction is important for determining the total flow rate (m^3/min), which is the cross sectional area perpendicular to the airflow (m^2) times the velocity (m/min) Therefore,

the cross sectional area is based on which way the air flows. If the air flows toward the wall, the cross sectional area is the area of the wall (width * height) If the air flows toward the floor, the cross sectional area is the area of the floor (width * length) The formulas for the total flow rates (Q_t) are as follows

If air flows to wall, Q_t = velocity * width * height

If air flows to floor, Q_t = velocity * width * length

- Total Flow Rate – This computation is provided for convenience so the user can see the total flow rate of the building based on the other inputs.

Economic Inputs Form

The economic input form shown in figure 4-9 will appear when the button labeled Economic Form is clicked in the main form.

Local Costs

- Natural Gas Input the cost of natural gas The cost of natural gas has a great deal of influence in the economic modeling section because all the thermal control devices which basically burn the VOCs assume the use of natural gas Units are in $/1000 ft^3 of natural gas.
- Electricity – Input the cost of electricity for the building in question. Units are in $/kilowatt-hour
- Steam – Cost of steam per 1000 gallon of water is needed for the carbon adsorption device to regenerate the carbon. This does not have a significant influence on the model Default is $6 00/1000 gal
- Active Carbon – Input $/lb of activated carbon. Default is $2 00/lb

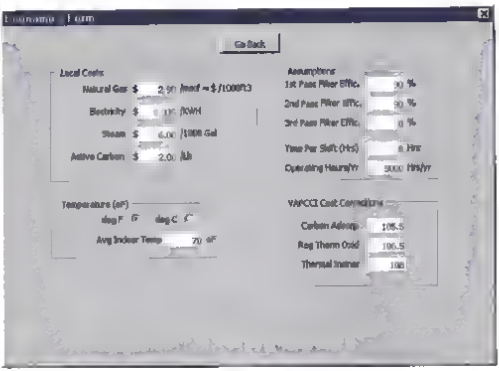

Go Back
Local Costs
Natural Gas $ 2.90 /mcf = $/1000ft3
Electricity $ 0.10 /KWH
Steam $ 6.00 /1000 Gal
Active Carbon $ 2.00 /Lb
Assumptions
1st Pass Filter Effic. 90 %
2nd Pass Filter Effic. 50 %
3rd Pass Filter Effic. 0 %
Time Per Shift (Hrs) 8 Hrs
Operating Hours/Yr 5000 Hrs/Yr
Temperature (oF)
deg F 0 deg C -17.8
Avg Indoor Temp 70 oF
VAPCCI Cost Corrections
Carbon Adsorp 105.5
Reg Therm Oxid 106.5
Thermal Incinor 100

Figure 4-9 Economic Form

Assumptions

- 1st Pass Filter – Input the filter efficiency for the filters that will be used in the recirculation system. The filter efficiency has a significant influence on particulate concentrations because the solid particulate in the recirculated air will be taken out with filtration. As the air passes the filters, the solid concentration in the air is reduced in proportion to the filters efficiency rating. Particle size is not a consideration to the model nor are changes in efficiency due to particles "caking" on the filter (assuming airflow remains the same...a filter will often become more efficient as particulates build up on the surface.) The model will simply multiply the concentrations by one minus

the filter efficiency (1-FE) to calculate the fraction of particulate that passes the filter If 100 mg/m^3 of aluminum is generated, and the filter efficiency is 95%, then, 5% or 5 mg/m^3 of aluminum will be recirculated back into the building 100% of the liquid fraction is assumed to pass the filters.

- 2nd Pass & 3rd Pass Filters – If a second or third series of filters is used then enter the efficiency of each. Sometimes a pre-filter is used over a main filter or a series of filters is used for added efficiency The model will multiply the efficiencies together to get the overall efficiency of a series of filters. For example, if two filters each have an efficiency of 95% then (1- 95)*(1- 95) = 0.25% will get through the filters If the overall efficiency of the filter series is already known, input the total efficiency under 1st Pass filter efficiency and leave the others blank
- Time/shift – Input the length of the shift time (typically 8-hours). The model does NOT adjust the OELs for shift time. OELs are based on an 8-hour day and must be adjusted if the shift length is longer The shift time is used to calculate the average exposure concentration over the length of shift If a product is generating a chemical concentration of say 100 mg/m^3 for two hours and nothing for the remainder of the day, the TWA in an 8-hour shift is about 25 mg/m^3 If the shift time was 10-hours, the TWA is 20 mg/m^3 All OELs are based on an 8-hour shift so the OEL must be lowered for a longer shift otherwise the exposure is under represented. See OSHA or ACGIH guidelines for directions on how to adjust OELs for shift times different than 8-hours.

- Operating Hours – Annual operating hours refers to the operation time of the recirculation system (hrs/yr – the recirculation and air control system is operating) It is used only in the economic portion of the model.

Average Indoor Temperature

Input the average temperature of the building in Celsius or Fahrenheit depending on which units are highlighted The average temperature is needed for the economic section of the model but its impact is small

VAPCCI Cost Corrections

The air control portion of this model is based on the EPA CO$T AIR model. The CO$T AIR model contains an index, called the Vatavuk Air Pollution Control Cost Index (VAPCCI) Each of the three technologies in this model is accompanied by a VAPCCI, which is an inflationary index published quarterly by the EPA Office of Air Quality Planning and Standards (OAQPS) Standards Development Branch. The index is intended to adjust for inflation specific to each control technology New VAPCCI numbers can be found on the EPA Internet site located at http //134 67 104 12/html/ctc/ctcsft.htm or follow the steps below

- Go To www.epa.gov/ttn,
- Select "Directory of TTN Sites",
- Select Control Technology Information "CTC",
- Select Downloading CTC Products under Documents/Software
- Select ESCA UP#X for latest VAPCCI indexes (X is the highest #)

The default in the model is for the 3rd quarter 1996 Input new VAPCCI numbers for Carbon Adsorption, RTO and Thermal Incineration if desired

Output Form

There are several outputs from the model. The output form, shown in figure 4-10, is intended to help organize and view the various outputs. This form appears right after the model is run or if the "Output Form" button in the Task-Product-Chemical Form is clicked. On this form, several output selections appear in the box. Click on any selection and the corresponding output will be displayed. While this Output Form is active, the Excel spreadsheets can be viewed but Excel will not be functional until the VBA input forms are closed. All functions in Excel such as printing will be disabled until the VBA input forms are closed.

Figure 4-10 Output Form

The arrows at the bottom of this form are provided to be able to move the cursor in the spreadsheets. To observe how various outputs change relative to recirculation, the arrows next to the "recirc level" box are provided to increase or decrease the recirculation level by increments of 10%. A brief description of each output is listed below in the order they appear on the form.

- TWA/OEL Graph – The Time Weighted Average (TWA) Concentration divided by either the OSHA PEL or the ACGIH TLV as shown in the formula below. The

$$\text{Relative TWA} = \frac{\text{TWA Concentration(mg/m3)}}{\text{TLV or PEL (mg/m3)}}$$

chemical with the highest relative TWA for each task is displayed on this graph. If the relative TWA exceeds 1.0, then the chemical's predicted concentration is over the OSHA PEL or ACGIH TLV. It is possible that another chemical is over the OEL but not be displayed on this graph, because only the highest relative TWA in the task is displayed. Tasks that have chemicals without an OSHA or ACGIH OEL are not plotted on this graph. This graph is cleared each time VBA forms is loaded. The model must be run again to re-created this graph.

- TWA/OEL Data – This is a more detailed spreadsheet for all relative TWA ratios. This spreadsheet lists all tasks, products and chemicals so that the user can see which products are major factors impacting occupational health. The recirculation level can be changed with the arrows at the bottom of the output form and this spreadsheet will automatically be updated. This spreadsheet is cleared when VBA forms is loaded.

- TWA in mg/m3 – This spreadsheet provides the actual TWA concentration in mg/m^3 for each chemical in each product. The recirculation level can be changed with the arrows at the bottom of the output form and this spreadsheet will automatically be updated. This spreadsheet is cleared when VBA forms is active.
- MAX/OEL Graph – Same as the relative TWA graph above except this graph displays the maximum concentration divided by either the STEL or the ceiling as shown below. If OSHA and ACGIH were selected, the most conservative STEL or ceiling is applied. This graph is cleared when VBA forms is loaded.

$$\text{Relative Maximum} = \frac{\text{Max Concentration (mg/m3)}}{\text{STEL or Ceiling (mg/m3)}}$$

- MAX/OEL Data – This is a detailed spreadsheet for relative maximum ratios. This spreadsheet lists the relative maximum concentrations for all tasks, products and chemicals so that the user can see which tasks and chemicals are major factors impacting occupational health. The recirculation level can be changed with the arrows at the bottom of the output form and this spreadsheet is automatically updated. This spreadsheet is cleared when VBA forms is loaded.
- MAX in mg/m3 – This spreadsheet provides the maximum steady state concentration in mg/m^3 for each chemical in each product without the STEL or ceiling involved. The recirculation level can be changed with the arrows at the bottom of the output form and this spreadsheet will automatically be updated.
- TWA & Max Graph Data – This is a summary spreadsheet of both the MAX/OEL and TWA/OEL ratios by recirculation. Only the highest relative TWA and relative

maximum in each task is listed here. The data in this chart is used to plot the relative maximum and relative TWA graphs. The information in this spreadsheet is cleared when VBA forms is loaded

- TWA & Max Task Sums – This spreadsheet displays the TWA and Maximum ratios for every chemical by task. It is different from the Max/OEL data and the TWA/OEL data because it does not show each product. This spreadsheet totals the products and displays the sum concentrations by chemical within each task. The recirculation level can be changed with the arrows at the bottom of the output form and this spreadsheet will automatically update. This spreadsheet is cleared when VBA forms is loaded.
- Top 4 Chem by Task – This spreadsheet contains graphs of the relative TWA and Maximum concentrations for the highest four chemical within a selected task. It allows the user to select a task and the four chemicals with the highest relative concentrations are plotted. Because the previous graphs only give the highest relative chemical concentrations for each task, other chemicals that may be of concern could be hidden from view underneath the highest chemical. This graph is intended to give the user a way to view the top four chemicals so that other significant chemicals are not ignored. To use this sheet, the model must first be run. Then, when the Outputs form appears, select "To Excel (Keep Outputs)". Select the spreadsheet named "Top 4 Chem" and press the "Change Task From >" button to select a task to be evaluated. A macro in Excel will collect the data and graph the results automatically.

At different levels of recirculation, chemicals may switch rankings. For example, the highest chemical at 30% recirculation may be the second highest chemical at 40% recirculation. The spreadsheet will show which chemical is at each

ranking but the user must be attentive to the switching. The graphs plot the highest chemical followed by the second highest etc but the graph will not indicate if there is a chemical switch. The user must check the raw data next to the graphs to detect a chemical switch.

- Fire/Explosion – This chart is to gain an understanding for the potential of a fire or explosion hazard. As recirculation increases and indoor air concentrations increase, the concern over fire hazard increases. This chart plots the sum of the maximum concentrations of all chemicals in each task. Many chemicals have a lower explosive limit (LEL) of 1% (or 10,000 ppm) or higher The LEL is the lowest concentration of vapour in air which will burn or explode upon contact with a source of ignition. An LEL of 1% is assumed for all chemicals in this evaluation. OSHA requires that indoor concentrations remain below 25% of the LEL (25% * 10,000 ppm = 2,500 ppm) It is often recommended that 10% of the LEL (10% * 10,000 ppm = 1,000 ppm) be used. Many LEL monitors are programmed to set off an alarm if 10% of the LEL is exceeded Therefore in interpreting this chart the user should keep the sum of the maximum concentrations of the chemicals in each task below 1 000 ppm.

To be sure all products are accounted for in the fire hazard analysis, an adjustment is made to products that are partially loaded For example, if the user enters only 50% of the chemical breakdown for a product, then the products maximum concentration is multiplied by 2 0 to adjust for the missing 50%. This adjustment insures that the fire hazard is not underestimated due to incomplete knowledge of the product s make-up

For this fire analysis, it is important to recall the assumption that the chemical concentrations are evenly distributed in the building (see Assumptions – Chapter 3). In reality, localized "hot spots" are common particularly near the emission source This is when concentrations build-up in one area of the building more than another area. This means that even though this chart indicates the LEL is not exceeded based on even distribution of the concentrations, the LEL may be exceeded in the hot spots It is for this reason that this chart is not intended to substitute for a properly detailed fire hazard evaluation where potential hot spots taken into account This chart is intended as a way to better understand how recirculation influences the probability of a fire or explosive hazard.

- Cost 10 Yr Cum – This is a graph of the cumulative cost over a 10-year period for the cost of controlling VOC emissions. The first year is usually the highest due to the capital cost of the equipment The increases in subsequent years is due to the annual operating cost of the system. It is assumed that the equipment has a 10-year life cycle Generally thermal incineration is more expensive in fuel consumption but the capital costs can be less while the Regenerative Thermal Oxidizer (RTO) is more efficient in fuel consumption but the start-up costs are higher A Carbon Adsorption Concentrator used with RTO uses the carbon to adsorb the VOCs and concentrate the pollutants going to the RTO The carbon adsorber with RTO can costs more up front, but the RTO can efficiently burn the more concentrated VOCs In some cases, carbon adsorption with RTO can achieve a self-sustaining burn, which does not require auxiliary fuel. The lowest line (usually Carbon with RTO) on this graph represents the lowest cost and therefore the best option. The recirculation level can be changed with

the arrows at the bottom of the output form and this graph is automatically update As the recirculation level increases, the exhaust airflow and the cost of treatment are reduced.

- Cost Annualized – This is an annualized cost graph at various levels of recirculation. The cost represents level payments over 10 years (not actual cash flows) This allows the user to compare the average cost at various recirculation levels. If any cost parameters are altered, this graph must be updated by clicking the "Press Here To Update this Chart" button in the top corner of this graph.
- VOC Output by Task – This is a pie graph representing the total annual pounds of VOCs output by task. This graph is intended to give the user a breakdown of the tasks to see which tasks contributes the most to VOC emissions
- Hours/Yr by Task – This is a pie graph representing the amount of time spent at each task annually This can help when deciding how to control workers' exposure.
- Inputs – Product & Chem – This sheet is the main input sheet where all tasks, products and chemical inputs are stored The general structure of this sheet is that all tasks and products are entered into rows with the first 26 columns being used for product or task attributes. The columns contain chemicals that make up the products and the first 34 rows contain chemical specific data. When a number is entered into the matrix, the model recognizes that the product in that row contains the chemical in that column. The number indicates the percentage of the chemical (in column) for that product (in row) An example of the spreadsheet layout is shown in table 4-4

Table 4-4 Spreadsheet Layout

			Chemical 1	Chemical 2	Chemical 3
			Chem data	Chem data	Chem data
Task 1	Product 1	Prod data	5	1	1
Task 1	Product 2	Prod data		20	
Task 2	Product 3	Prod data	15	50	
Task 2	Product 4	Prod data		80	
Task 2	Product 5	Prod data	60		5

This sheet is protected when the user enters Excel because the model uses many pre-named cells that, if altered, would corrupt the model. This sheet becomes unprotected when the VBA input forms are loaded so that new entries can be made

- Inputs – General – This spreadsheet has miscellaneous inputs such as building dimensions, velocity, airflow, etc. It is protected when Excel is active and unprotected when the VBA input forms are loaded.
- Inputs – Control Costs – This spreadsheet contains the EPA models of the three different treatment options. It computes the cost of treatment for VOCs and provides the data for the cost graphs.
- To Inputs (Clears Outputs) – Allows the user to go back to the VBA input forms. The output form is closed and the outputs in spreadsheets are cleared. There is a slight hesitation when this selection is made because the output spreadsheets are cleared.
- To Excel (Keeps Outputs) – Closes the VBA forms and goes directly to Excel. This option will keep all outputs so the user can view the data while in Excel. To get back to VBA input forms click on the "Back to Visual Basic Forms >" found on the top of nearly every spreadsheet in Excel. The user should always save while in VBA input

forms (not in Excel) and make a back up copy of the model in case an inadvertent entry is made that prevents the model from running

- Recirc Level – Below the output selections in the Output form is a box labeled "Recirc Level." By clicking the arrows next to it, the user can increase or decrease the recirculation level in the model. The graphs or sheets that are sensitive to recirculation will then change to provide feedback on the effect of recirculation to the various outputs.
- Moving – Because Excel functions are disabled when VBA input forms are loaded and some of the spreadsheets can be quite large, the arrows are provided to allow movement in the Excel spreadsheets from the Output form. The arrows do not appear if a graph has been selected because cursor movement is not necessary. The user can adjust the speed of the movements in Excel from slow (one cell at a time) to fast (10 cells at a time). At times it may appear that the cursor is not moving. That is because there are some unnecessary rows and columns that are hidden. The arrows allow the user to move by increments so if there is a large section of rows or columns that are hidden, the movements occur within the hidden cells. This makes it appear that the cursor is not moving until the cursor moves out of the hidden cells

Program Errors

If an error is encountered while the VBA input forms are running, the program will likely open the Visual Basic Debugger which will highlight the area of the code that the error has occurred. A popup menu will appear with the selections END or DEBUG. At this point hit END, which closes the Visual Basic Debugger. After END is selected, the

Visual Basic Debugger may still be showing. To put the Excel model back on top, just select the Excel file on the Start Bar. If DEBUG is selected, the program will allow the user to alter the code and this is NOT recommended. The code is quite complex and a small change can disable the model. If the bug is believed to have occurred due to something recently entered, close the model WITHOUT saving the model. This may prevent a persistent problem that may be difficult to find. Otherwise, save the model in VBA (use a different file name in case the problem persists) and close the model. Restart the model by opening up the Excel file as usual and continue. If the problem persists, the file may have been corrupted and it is necessary to restart with a backup copy. Always make backup copies of the model under different names because any file can become corrupted and not much can be done beyond that point.

CHAPTER 5
CASE STUDY HILL AFB PAINTING OPERATIONS

Introduction

This chapter will detail the C-130 Painting Process at Hill AFB and discuss each step in the process. A site visit was performed on June 8-13, 1997, and much of the information reported in this chapter was gathered from this site visit. The primary sources of information were through document review at the painting facility and at the Hill AFB Bioenvironmental Engineering Office. The various tasks were observed and interviews were conducted with the assistant shop supervisor,[3] various painters and Environmental Management personnel.

Hill AFB

Hill AFB located in Salt Lake City, UT, is the host base for the Ogden Air Force Logistics Centers (ALC). The Ogden ALC is one of five major ALCs in the Air Force. They perform maintenance, repairs and logistics management on the C-130 Hercules, the F-16 Falcon, F-18, F-4, and all strategic intercontinental ballistic missiles. In 1995, a total of approximately 22,000 were employed at Hill AFB including 4,400 military, 9 400 government employees. Contractors and reservists make up the remainder. Hill AFB has a $1.3 billion budget with 1,475 buildings and has one of the single busiest runways in the

[3] Assistant Shop Supervisor was Mr Brent Campbell

Air Force Hill AFB is also is considered one of the top ten VOC emission sources in Davis County, which is a non-attainment area for ozone (Parsons, 1995)

Background – C-130 Painting

There is a total of 684 C-130 aircraft in the Air Force inventory as of May 1996 located throughout the world. Every C-130 requires a complete overhaul including painting every 66 months (5.5 years) If evenly distributed, 124 Air Force aircraft per year need to be serviced not including Navy C-130s Hill AFB paints 50 aircraft annually The Hill AFB painting process takes place in a large paint booth located inside building 270 There are ten people assigned per shift with three 8 hour shifts working around the clock They operate five days a week but they often work overtime on Saturdays and sometimes Sundays to complete approximately 50 C-130s per year It takes five to six days to paint an Air Force C-130 and eight to nine days to complete a Navy C 130

How Tasks Are Determined

The C-130 painting process is flowcharted to help determine individual tasks If the tasks are substantially different, such as differences in application rates or differences in the types of products used, a unique task is created For example, an aircraft that arrives at building 270 can either be painted or stripped down to the bare metal. Each aircraft is allowed to have only two coats of paint before they have to be stripped down. Therefore, of the 50 planes, an average of 25 will be painted and 25 will be stripped down. During the alodine task (a metal pretreatment) the same alodine solution is used for all planes. However, a stripped aircraft requires 80 gallons and a painted aircraft requires about four gallons. There is also a difference in the amount of time it takes to

alodine a stripped aircraft versus a painted aircraft. These differences create the need to separate the alodine task for a stripped aircraft versus a painted aircraft. The different application rates will yield different air concentrations (Battelle, 1995, Parsons, 1995).

Also, of the 50 C-130s serviced per year approximately 40 are Air Force and 10 are Navy planes. Of the 40 Air Force planes, about four per year require a green camouflage finish, while the remaining 36 require a gray polyurethane finish. The Air Force gray. Air Force camouflage and Navy planes each require different paint products. Table 5-1 shows the breakdown of the 17 major tasks identified and the six different types of C-130 aircraft typically painted by the Hill AFB facility. The numbers in the table correspond to the number of times each task is performed per year. The totals are added in the last column.

Task Breakdown for Painting Process

There are 17 major tasks involving products containing chemicals that will be evaluated with respect to recirculation. There are other tasks such as taping, cleanup and general preparations that will not be evaluated because they do not involve hazardous chemicals. However, scuff sanding occurs with orbital sanders on a painted aircraft to rough the surface for painting. Although a chemical product is not added to this task, there can be significant exposures to hazardous metal dust from the sanding operation (cadmium from bolts and chromium from old primer paints). The mathematical nature of this model can not account for such tasks and air sampling is the only way to determine indoor air concentrations from task that do not consume a product. The tasks breakdown

Table 5-1 Breakdown of Number of Tasks Per Year

Type of Aircraft	AF Paint (Gray)	AF Strip (Gray)	AF Paint (Camo)	AF Strip (Camo)	Navy Paint	Navy Strip	Annual Tasks Totals
# of Aircraft Types/Yr	18	18	2	2	5	5	
Wash	18	18	2	2	5	5	50
Bright		18		2		5	25
Enzyme	18		2		5		25
Alodine Strip		18		2		5	25
Alodine Painted	18		2		5		25
MEK Wash	18	18	2	2	5	5	50
AF Sealer		18		2			20
Navy Sealer						5	5
AF Prime strip		18		2			20
AF Prime painted	18		2				20
Navy Prime					5	5	10
AF Poly (Gray)	18	18					36
AF Poly (Camo)			2	2			4
Navy Poly					5	5	10
AF Stencil	18	18	2	2			40
Navy Stencil					5	5	10
Soil Barrier	18	18	2	2	5	5	50

is flowcharted in figure 5-1 in the order in which they are performed. A description of each task is also provided and a list of products used in each task follows the descriptions

1. Wash – The wash task is the first step performed on every aircraft. A mixture of soap and water is sprayed onto the aircraft and then hand washed with brushes. The aircraft is then rinsed with water. It takes ten people about four hours to accomplish this task using 12.5 to 25 gallons of soap.
2. Brightener – The Brightener task is an acid application performed on stripped aircraft to remove any oxidation that has occurred on the metal. A 1-1 part mixture of water

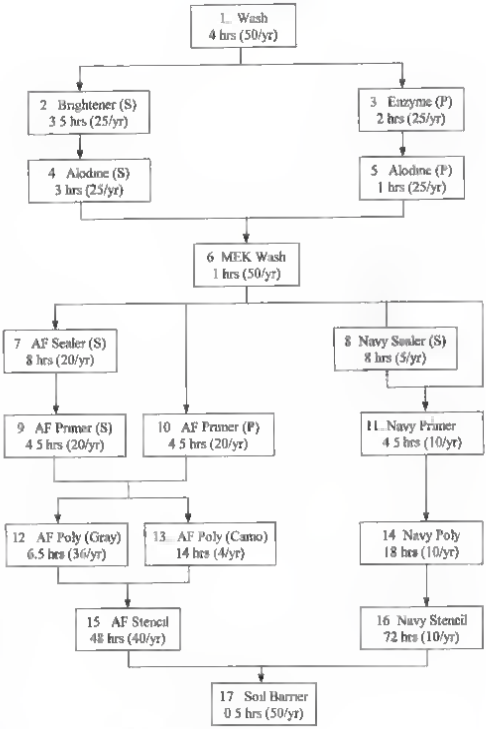


Figure 5-1 C-130 Painting Process Flowchart

and Brightener is sprayed onto the aircraft and then scrubbed to remove oxidation. The aircraft is then rinsed off and the waste flows down an industrial sewer for treatment. It takes ten people three to four hours to accomplish and about 50 gallons of the mixture is used per aircraft.

3 Enzyme – The Enzyme task is a treatment for an aircraft with a previous coat of paint. After the surface of the paint has been scuff sanded with orbital sanders, a water-based enzyme solution is used to partially digest the paint surface. Five gallons of enzyme is added to 45 gallons of water and the mixture is sprayed on and then scrubbed for even distribution. The aircraft is then rinsed off and rinsate flows down an industrial sewer for treatment. It takes ten people about two hours to accomplish this task.

4 Alodine Strip – Alodine is a metal pretreatment containing chromates, which bonds with the aluminum surface and facilitates proper adherence between the metal and the primer paint. If alodine is not applied to all metal parts, the paint will not adhere properly. A slight color change can be seen on metal treated with alodine indicating a proper application. The alodine is sprayed on, allowed to sit for a few minutes and the excess is then rinsed off with water. The Alodine Task on a stripped aircraft requires 80 to 100 gallons of alodine and takes ten people three hours to accomplish.

5 Alodine Painted – The same process and product is used here as for Alodine on a stripped aircraft only far less alodine is used. It takes about one hour and only four to

five gallons is needed to touch up areas where bare metal is exposed from scuff sanding

6 MEK Wash – The final preparation before painting is a wash down using either MEK or a 1:1 mix of MEK and Toluene. If pure MEK evaporates too quickly due to environmental conditions, toluene, which has a much slower evaporation rate is mixed in (1:1 ratio) to slow down the evaporation. The solvent solution is applied primarily on the engines and belly of the aircraft. The engines frequently leak hydraulic oil and this solvent wash down is used to clean these surfaces prior to painting. This task is performed on all aircraft. It takes about one hour and five to six gallons of either solution are used. Masking and inspections occur at this point.

7 AF Sealer – The Sealer tasks are performed on a stripped aircraft only to restore the anti-slip walkways on the top of the wings and fuselage. These are areas designated for aircrew to walk on so they require special treatment. The areas are primed and painted using rollers. The Sealer Compounds are diluted with MEK and toluene to thin the mixture. The entire task takes four to five people about nine hours to complete but some products listed below are applied at overlapping times and the times are relative to the application rate of that particular product

8 Navy Sealer – The Navy Sealer is similar to the Air Force Sealer except different products and quantities are used

9 AF Prime (S) – At this point, the aircraft has been prepared, masked and is ready for a coat of primer paint. The (S) indicates a stripped aircraft. The primer contains chromate that will help adhere the polyurethane topcoat to the aluminum surface Several paints contain two parts, an activator and a base, which must be mixed in a separate mixing room before application. The ratio for the Air Force primer paint is a 1 8 ratio of activator to base (most others are 1 3) The paint is then loaded into 5-gallon pressure pots. There is typically a mixer, four painters and four hose-pullers, which help manipulate the hoses for the painters. The paint is sprayed on. Various lift stations, elevators and floor creepers are used to reach the many surfaces af the aircraft It takes four to five hours and 20 to 25 gallons to complete an aircraft. When the job is finished, leftover paint is poured into a storage drum for later disposal. Each pot is then cleaned with either one to two gallons of polyurethane thinner ar MEK for the next application. The aircraft is tacky after two hours but is allowed to dry for eight to ten hours depending oo environmental conditions before the topcoat is applied (the booth gets colder in winter which slows the drying process) Note If a paint has two parts, each part is treated as a separate product in the model and the amount used is adjusted with respect to the total amount used, 20 gallons at 1 8 is 2.2 gallons activator and 17 8 gallons base)

10 AF Prime (P) – Similar to Air Force Priming on a stripped aircraft except (P) indicates an aircraft with paint left on. Different products and application rates are used on a stripped aircraft versus a painted aircraft (see appendix A for a list af products used)

11 Navy Prime – Similar to Air Force Priming on a stripped but different products and application rates are used (see appendix A for a list of products used)

12. AF-Poly (Gray) – The gray polyurethane topcoat is the most commonly required paint scheme, however, this can change based on needs. During Operation Dessert Storm several were converted to a desert camouflage paint scheme. Also, some reserve planes are painted with forest green camouflage. As with the primer paints, the paint is mixed (1 3 ratio), loaded into pressure pots, and four painters spray the paint onto the aircraft. Leftover paint is poured into a waste drum. It takes 40-45 gallons of polyurethane to cover the aircraft and the entire task takes eight hours including preparations and cleanup. The paint is allowed to set for eight to ten hours.

13. AF-Poly (Camo) – Only four out of 50 aircraft were painted with a camouflage scheme in 1995. A gray coat is first applied on the entire aircraft and allowed to dry for eight to ten hours. Then decals are used to help painters apply and blend two shades of green in certain areas. The gray application takes six hours with four painters and each application of green takes four to five hours with two painters.

14 Navy-Poly – Ten planes out of 50 were Navy planes in 1995. The Navy has only one paint scheme for all planes and it entails three different shades of gray (light, medium, dark). The light gray is painted on the entire aircraft using 40-45 gallons and takes about four hours. Then 20 gallons of medium gray is painted on the sides of the aircraft and another 20 gallons of dark is painted on the top of the aircraft. Three to

four hours of drying time is needed in between each application and painting takes four hours with three painters.

15 AF-Stencil – In the Air Force stenciling task, computer generated templates are placed on the plane. This takes ten people about eight hours to complete Then all painters use a flat black paint to cover each template The entire task takes three or four, eight hour shifts. Roughly one shift to apply templates, another shift to paint and another to peel off the templates Small eight-ounce paint guns are used to apply a total of only four to five gallons of paint Although stenciling a camouflaged aircraft takes a little less time (two to three shifts), stenciling a gray aircraft versus a camouflaged aircraft were determined to be similar enough to keep just one Air Force stenciling task.

16 Navy –Stencil – The Navy stenciling task takes substantially more time (nine shifts or 72 hours) due to the fact that there are over 1000 individual templates used (versus 300 on an Air Force plane) The same three types of gray polyurethane paints used in the topcoat are also used in the stenciling but different shades are used on different background surfaces (dark on medium, medium on dark and light on medium) Black and silver are also used in some locations and the propeller tips are painted with red and white

17 Soil Barrier – Finally a soil barrier is sprayed into the flap wells where the engine's exhaust may strike parts of the wings. This is to protect these surfaces exposed to the high heat and pressure from the engines.

Other Inputs and Assumptions to the C-130 Painting Process

The amount of overspray in the painting tasks plays a role in how much of the solid fractions of the paint are released to the air. The overspray in all painting operations is assumed to be 50%. The air atomized spray system used in the C-130 painting facility has an overspray range of 32-88% with an average of 60% (Ayer and Hyde, 1990). Generally, a large flat painting surface (i.e. aircraft) would produce less overspray as opposed to smaller complex surfaces (i.e. table legs, poles). Due to the experience of the painters and the large surface of the aircraft a slightly smaller value of 50% overspray is assigned to painting tasks rather than the average of 60%. The wash, brightener, enzyme and alodine tasks which are assigned a 10% overspray. A lower overspray is used because these tasks do not use the air atomized spray system which is under high pressure. The droplets created in these tasks are large (similar to that of a garden hose).

Rinsing a product after application will effect the quantity of liquid chemicals available to evaporate into the air. All products used in the painting tasks have "no rinsing". The wash, brightener, enzyme and alodine tasks are rinsed. The wash, brightener and enzyme tasks are assumed to leave 5% of the product in the booth (95% rinsed away) and the alodine tasks are assumed to leave 10% in the booth (90% rinsed away). The reason for the difference is because the alodine solution is allowed to sit on the aircraft for a few minutes before it is rinsed away. All the products in these tasks, which are rinsed, are water-based products. Therefore, the influence of rinsing is negligible because rinsing effects only the liquid chemical concentrations which is water in

this case Various other inputs that were used in the model for this demonstration are listed in table 5-2

Table 5-2 Miscellaneous Information Used for Demonstratioo

FORM	CATEGORY	QUANTITY	SOURCE
Building	Height of Booth	11 m	Parsons, 1995
Form	Width of Booth	30 m	Parsons, 1995
	Length of Booth	30 m	Parsons, 1995
	Air Velocity	30 5 m/mm	BEE Survey, 1996
	Airflow's Towards	Wall	By design
Economics	Natural gas price	$ 2 90/1000 ft^3	Parsons, 1995 2-6
Form	Electricity Price	$ 0 035/kWh	Parsons, 1995 2-6
	Steam price	$ 6 00/1000 lbs	Parsons, 1995
	Carbon price	$ 2 00/lb	Parsons, 1995
	Average Indoor Temp	70 ^{o}F	Site Visit Interview
	1st Pass Filter Efficiency	90 %	Future design
	2nd Pass Filter Efficiency	90 %	Future design
	3rd Pass Filter Efficiency	0 %	Future design
	Time per Shift	8 hours	Site Visit Interview
	Operating hrs of Control	5000 hours	Site Visit Interview
	VAPCCI Carbon Adsorption	105 5	Vatavuk
	VAPCCI Regenerative Thermal Oxidizer	106 5	Vatavuk
	VAPCCI Thermal Incinerator	108	Vatavuk

Products Used in Painting Process

The products for each of the tasks along with usage rates can be found in Appendix A. The information contained in the product list was assembled during the site visit using paint inventory logs and an interview with the shop supervisor Thus information was cross-referenced with a physical inventory in the supply room. Also, the

chemical breakdown of each product was obtained from Material Safety Data Sheets (MSDSs) Each MSDS was acquired from the following sources in order of preference

- Depot Maintenance-Hazardous Materials Management System (DM-HMMS) – database used at Hill AFB for MSDSs,
- Hazardous Material Information System (HMIS) on CD-ROM – AF database of MSDSs,
- Manufacturers – missing MSDSs were obtained directly from manufacturers.

Chemicals Used in Painting Process

There were many sources used to assemble the chemical database which contains over 1300 chemicals (see Chapter 4 for list of sources) This database was used to extract chemical information for the 54 chemicals found in the products used at the Hill AFB paint facility The chemicals found in the various products used at the paint facility are listed in table 5 3 The column heading definitions for the chemical list are as follows

- CAS – Chemical Abstract Service (CAS) Registry Number to uniquely identify the chemical
- Name – IUPAC Chemical Name (common names used as appropriate)
- # of Prod Number of painting products that the chemical is found
- Avg % – The average percent make-up for the products the chemical was found in
- STEL Ceil – Lowest STEL or ceiling between OSHA and ACGIH (mg/m^3)
- TLV – ACGIH 8-hour TWA limit (mg/m^3)
- PEL – OSHA Permissible Exposure Limit (mg/m^3)
- MW – Molecular Weight
- L/S – Liquid or Solid at room temperature

Table 5-3 Chemical List in Painting Process

CAS	Name	# of Prod	Avg %	STEL Ceil	TLV mg/m^3	PEL mg/m^3	MW	L/S
95636	1 2 4-Trimethylbenzene	1	10%		123		120	L
123546	2-4 Pentanedione (acetylacetone)	12	5%				100	L
111762	2 Butoxyethanol	2	0 55%		121	240	118	L
110123	5-Methyl-2-hexanone	2	17%		234	475	114	L
7429905	Aluminum (total dust)	2	5%		10	15	27	S
1344281	Aluminum Oxide (Total Dust)	1	25%		10	15	102	S

Table 5-2 Continued

CAS	Name	# of Prod	Avg %	STEL Ceil	TLV mg/m³	PEL mg/m³	MW	L/S
100516	Benzyl alcohol	1	*Unk				108	L
103833	Benzyl Dimethylamine	1	Unk				135	L
80057	Bisphenol A	1	10%				228	S
1317653	Calcium Carbonate (Limestone)	10	5%		10	15	100	S
14307336	Calcium dichromate	2	20%	0.126	0.123		256	S
1333864	Carbon black	2	5%		3.5	3.5	12	S
1333820	Chromium trioxide	2	5%	0.1	0.096		100	S
108941	Cyclohexanone	4	25%		100	200	98	L
61790532	Diatomaceous earth, uncalcined	2	5%		3		60	S
77587	Dibutyltin Dilaurate (as tin)	13	0.10%		10.7	10.7	631	S
763699	Ethyl 3-Ethoxypropionate	25	13%		300		146	L
100414	Ethylbenzene	27	6%		434	435	106	L
50000	Formaldehyde	2	0.01%	2.4		0.9	30	L
822060	HDI (free monomer)	12	0.50%		0.034	0.034	168	L
28182812	HDI (poly)	11	40%				168	L
4035896	HDI (biuret)	8	35%				479	L
110190	Isobutyl acetate	2	30%		713	700	116	L
67630	Isopropyl alcohol (2 Propanol)	2	0.01%		983	980	60	L
13423615	Magnesium chromate	3	13%	0.14	0.135		140	S
110430	Methyl amyl ketone	3	8%		233	465	114	L
78933	Methyl ethyl ketone	30	42%		590	590	72	L
108101	Methyl isobutyl ketone	22	18%		205	410	100	L
107879	Methyl Propyl Ketone (MPK)	5	13%		705	700	86	L
101688	Methylene bisphenyl isocyanate(MDI)	2	5.00%	0.2	0.051		250	S
1330207	Mixed xylenes	26	6%		434	435	106	L
127195	n,n-Dimethylacetamide	2	25%		36	35	87	L
68122	n,n-Dimethylformamide	1	30%		30	30	73	L
140318	n-Aminoethylpiperazine	1	10%				129	L
64742956	Naphtha	15	4%				100	L
8030306	Naptha (Rubber Solvent)	1	35%		1590	400	110	L
123864	n-Butyl acetate	27	7%		713	710	116	L
71363	n-Butyl alcohol	2	0.01%			300	74	L
7697372	Nitric acid	1	4%		5.2	5	63	L
25154523	Nonylphenol	1	0%				220	L
7664382	Phosphoric acid	1	5%		1	1	98	L
13746662	Potassium Ferricyanide	1	Unk			11	329	S
107982	Propylene glycol monomethyl ether	3	1%		369		90	L
78922	sec-Butyl alcohol	1	25%		303	450	74	L
14464461	Silica, cristobalite	2	5%		0.05	30	60	S
14808607	Silica, quartz	3	12%		0.1		60	S
10588019	Sodium dichromate	2	10%	0.131	0.126		262	S
7789062	Strontium Chromate	6	22%	0.204	0.002		204	S

Table 5-2 Continued

CAS	Name	# of Prod	Avg %	STEL Ceil	TLV mg/m^3	PEL mg/m^3	MW	L/S
14807966	Talc, Non-asbestiform (< 1% Silica)	2	5%		2	2	379	S
61788327	Terphenyls (Hydrogenated)	2	5%			4 9	238	S
13463677	Titanium dioxide (total dust)	3	7%		10	15	80	S
108883	Toluene	28	15%	1128	188	750	92	L
112243	Triethylenetetramine	1	Unk				146	L
7732185	Water	Unk	Unk				18	L

* Unk indicates the quantity is unknown

Due to the variety of chemicals, only a few significant chemicals will be discussed in detail.

Chromium

Chromium is among the most toxic chemicals involved in the painting process Chromium is a hard, steel-gray metal which is highly resistant to oxidation. Chromium is the sixth most abundant element in the earth's crust The most common three valence states of chromium are Cr^0 (metal), Cr^{3+} and Cr^{6+} The trivalent chromium (Cr^{3+}) and hexavalent chromium (Cr^{6+}) are the most biologically significant Cr^{3+} is actually a required micronutrient at 0 05-0 2 mg/day but higher doses can be toxic (ATSDR, 1990) Cr^{6+} is the most toxic form of chromium and is more easily absorbed through the inhalation, ingestion and dermal routes (Klaassen, 1986 597) Strontium chromate contains Cr^{6+} and is the most toxic chromium containing compound. All the primer paints in the C-130 painting process contain anywhere from 20-25% strontium chromate The alodine solution contains 5% of chromium trioxide (CrO_3) which also contains Cr^{6+}. The OSHA ceiling limit for strontium chromate is 0 2 mg/m^3 (0 1 mg/m^3 as CrO_3) The ACGIH TLV for strontium chromate is 0 002 mg/m^3 (0 0005 mg/m^3 as Cr) The OSHA

ceiling for chromium trioxide is 0 1 mg/m^3 and the ACGIH TLV is 0.1 mg/m^3 (0 05 mg/m^3 as Cr).

The chromates in the Cr^{6+} valence state are good bonding agents to adhere the polyurethane topcoat to the aluminum fuselage and there are no good substitutes for the chromates. Stronium chromates work especially well as a bonding agent in the primer paints. Informal tests performed on primers containing other chromium salts or no chromate at all have resulted in poor adhesion and more frequent re-painting.

Cr^{6+} is a strong oxidizer that can cause local ulcerations, liver and kidney damage and is linked to a higher incidence of lung cancer (Grohse et al. 1955) Dermal and lung exposure to Cr^{6+} can cause local ulcerations at the point of contact Acute systemic effects include acute necrosis of liver tissue. Also, necrosis occurs in the proximal tubules of the kidneys, in an area responsible for glucose reabsorption. This progresses to a condition called Glucosuria and ultimately kidney failure (Ballantyne, 1995 451) Chronic exposure to Cr^{6+} has been linked to lung cancer and the International Agency for Research on Cancer (IARC) lists Cr^{6+} as a known human carcinogen. In an epidemiological cohort study with people who worked for more than one year at a chromium production plant from 1931-1949 the incidence of lung cancer was 18 2% whereas 1 2% was expected Several other studies involving workers in the chrome plating and chromium pigment industries suggest similar results (ATSDR, 1990)

Hexamethylene Diisocyanate (HDI)

Polyurethane paints contain diisocyanates, which crosslink to form the polyurethane structure in the cured paint. The diisocyanates are typically pre-polymerized,

which links them together to form heavier compounds. This reduces the volatility of the compound, presumably making them safer to use. The free monomer form of the diisocyanates is still present and is thought to pose the greatest health risk. However, the polymerized isocyanates have received attention recently because paint aerosols containing the less volatile polymers can still be inhaled (Fortrast and Carpenter, 1990). It has also been shown that the polymers, which still have reactive isocyanate groups (-C=N=O), can create respiratory disorders similar to the free monomer form (Streicher et al., 1994).

The paints used on the C-130 aircraft contain hexamethylene diisocyanate (HDI). The paints contain 30-45% of the polymer form and up to 0.5% of the free monomer form of HDI. The two-component paint system is mixed together just before application. The activator and the base are mixed allowing the isocyanate crosslinking to occur. The free monomer and to some extent the polymer form of HDI is a strong sensitizing agent (Rudinski). They can cause occupational asthma if chronically exposed to even small concentrations of HDI (Fortrast and Carpenter 1990). Currently OSHA and ACGIH do not have an OEL for the HDI polymer but both have a TWA limit of 0.034 mg/m^3 for the free monomer HDI.

Besides the controversy over the hazards of the HDI-polymer, there are several problems with the sampling methods for isocyanates. Isocyanates can exist in the air as a vapor or as an aerosol (droplets). Current sampling methods usually involve collection on a filter or impinger that contains a derivitizing agent. The derivitizing agent converts the volatile isocyanates into a non-volatile form. This works reasonably well for the free monomer vapors but the pre-polymerized isocyanates in the paint droplets are overlooked. For example, the impinger method collects 90% in the particle size range of 0 to 2.8

microns However, particle sizes during spray applications start at 10 microns, which are largely missed by the impinger collection technique. People can readily inhale particle sizes up to 60 microns. Particle sizes above 10 microns are too large to get into the lungs However, the larger particles from 10 to 60 microns can deposit in the nasal cavity where isocyanates can still do damage Also, many paints today have inhibitors that bind the isocyanates until the base and activator are mixed. The binding agent also inhibits the derivitizing agent used in the collection method, which further underestimates isocyanate concentrations Therefore sampling methods underestimate the total isocyanate groups that can cause a harmful effect A modified sampling procedure using an indirect approach has been used in sampling for isocyanates. The procedure requires air sampling for a pigment in the paint and multiplying the result by the isocyanate to pigment ratio in the paint (Poitrast and Carpenter, 1990, Streicher et al , 1994, Rudzinski and Pin, 1994 and Rudzinski et al., 1995)

The model in this study estimates the isocyanates concentrations based on mass balance calculations using the quantity of isocyanates found in the paints Therefore, the sampling errors mentioned above do not influence the model's predictions. However, because there are no OEL standards for the HDI-polymers, only the relative concentrations for the monomer are shown not the HDI-polymers

Methyl Ethyl Ketone (MEK)

MEK is not as toxic as chromates or isocyanates but they appear as the highest chemical in a few tasks MEK is used in a wide variety of products such as glues, paints and cleaning solvents because it dissolves many substances MEK is used frequently in the painting process In the painting process, it is used to clean the paint guns, it is added to

the sealer compounds for thinning and it is used to clean the aircraft in the MEK wash task. The painters add a MEK/toluene mix at times for thinning paints.

The health effects of MEK (2-butanone) inhalation include irritation of the nose, throat, skin, and eyes. No person is known to have died from exposure to MEK but animal studies show loss of consciense and death at very high concentrations. When ingested, mild kidney damage and nervous system damage has been observed in animal studies. MEK is not classified as a carcinogen. The OSHA and ACGIH TWA limit for MEK is 590 mg/m^3 (200 ppm), with an ACGIH STEL of 886 mg/m^3 or 300 ppm (ATSDR, 1992, NIOSH, 1990)

Toluene

Like MEK, toluene appears as the highest chemical in several tasks and it is frequently used in the painting process. Similar to MEK, toluene is used in the painting process to clean, thin paints and wash the aircraft. Toluene is found in many products to include paints, fuels, fingernail polish, adhesives and some printing solutions. Toluene evaporates more slowly then MEK. The painters thin the paints using more toluene if a product is drying too quickly or they use less toluene if a product is drying too slowly.

Low-to-moderate levels of toluene from long-term exposure can cause fatigue, confusion, weakness, memory loss, nausea and even hearing loss. Inhaling a high level of toluene in a short time can cause a feeling of being light-headed, dizzy, or sleepy. At very high levels (2000 ppm) it can cause unconsciousness, and even death. Repeated exposure to high levels can cause permanent brain damage, vision and hearing problems, and loss of muscle control. Toluene can also damage the kidneys. Babies can have neurologic problems and if mothers breathe a high level of toluene during pregnancy. Toluene is not

listed as a carcinogen. The OSHA TWA limit for Toluene is 750 mg/m^3 (200 ppm) with an OSHA ceiling of 1130 mg/m^3 (300 ppm). The ACGIH TWA limit is 190 mg/m^3 or 50 ppm (ATSDR, 1994, NIOSH, 1990)

Methyl Isobutyl Ketone (MIBK)

MIBK (sometimes called MIK) is a solvent found in many paint products. MIBK is the has the highest relative maximum concentration in several tasks. The health effects of MIBK are similar to that of toluene with dizziness, respiratory irritation, nervous system depression etc In addition, MIBK can potentially cause causing liver and visual abnormalities at higher concentrations. MIBK is not a listed carcinogen. The OSHA TWA limit for MIBK is 410 mg/m^3 (100 ppm) The ACGIH TWA limit is 205 mg/m^3 (50 ppm) with an ACGIH STEL of 307 mg/m^3 or 75 ppm (Klaassen, 1986, NIOSH, 1990)

CHAPTER 6
MODEL VALIDATION

In this chapter, a validation of the model is performed to test the models predictive accuracy. The Hill AFB painting facility is used as the test site. The economic portion of the model is compared to vendor's quotes using data from the Hill AFB facility. The air concentration predictions are compared to actual air sampling data taken at the Hill AFB paint facility for chromium and isocyanates. These sampling results are compared to the 0% recirculation rate predictions from the model because the sample are taken before the recirculation system is built. Also, to help understand the impact of the each variable on the concentration predictions, a sensitivity analysis using Crystal Ball 4.0 is provided in this chapter. Crystal Ball is software designed to work with Excel and performs simulations using probabilistic techniques. This is explained in more detail below. Also a qualitative sensitivity analysis is provided on all input variables to give a more complete understanding of the variable interactions on the economic and concentration outputs.

Vendor Cost Quotes

Separate vendors dealing with VOC control devices were contacted to obtain quotes to purchase and install an air control device at Hill AFB, Building 270. The purpose was to compare the COST AIR predictions in control costs to actual vendors quotes. Three different technologies were requested: Regenerative Thermal Oxidation (RTO) with Carbon Adsorption Concentrator, RTO only and Thermal Incineration. The

product list was provided to the vendors (Appendix A) detailing usage rates of the products and VOC content etc. The information shown in table 6-1 was provided to each vendor. The vendors were requested to send a written quote on three separate airflows at 355,000 cfm, 177 500 cfm and 35,500 cfm corresponding to 0% 50% and 90% recirculation levels.

Table 6-1 Utility Costs

Annual Operating Hours	5000 hours
Electricity Price	$0.035/KW-hour
Natural Gas Price	$2.90/1000 ft^3
Steam Price	$6.00/1000 lbs

Economic Validation

In comparing the EPA CO$T AIR Model and the actual vendors quotes, it was quickly determined that the CO$T AIR Model was predicting high for the RTO technology. According to conversations with vendors, the main reason for this is that the growth of demand for RTO units has increased substantially in the mid-1990s. Increased competition and modular designs have reduced the base price of an RTO unit in the late 1990s compared to the late 1980s. The EPA CO$T AIR assumption is that the RTO unit costs roughly $22.20 per cfm of air but current industry standards are closer to $15/cfm. The model was adjusted to $15/cfm to account for this change. After this adjustment, the model's cost predictions for the RTO and the RTO with carbon adsorption was more reflective of industry costs. Table 6-2 is a list of vendors contacted and table 6-3 is a list of quotes with comparisons to the models predictions.

Table 6-2 Vendors Contacted

Vendor Name	Address	Phone	Fax
Rsaco, Inc	Somerville, NJ	908-685-4238	908-685-4181
Vara, Intl	Vero Beach, FL	561-567-1320	561 567-4108
DURR Industries	Plymouth, MI	313-207-8500	313-207 8930
Englehard Process Emission Sys	Southfield, MI	800-437-1488	248-437-3807
McGill Air Clean	Columbus, OH	614-443-0192	614-445-8759

Table 6-3 Vendor Air Control Costs

Company		RTO+CA 0%	RTO+CA 50%	RTO+CA 90%	RTO 0%	RTO 50%	RTO 90%	Thermal Incineration 0%	Thermal Incineration 50%	Thermal Incineration 90%
Rsaco	Capital	3,275	1 920	800	5,900	2 770	630			
Rsaco	Gas/El	102	51	11 2	1 050	525	62			
Vara	Capital	5,375	2,875	780						
Vara	Gas/El	117	59	16						
Durr	Capital	7,000	3,600	1 000	7,200	3,100	950	5,800	2,500	500
Durr	Annual	250	125	30	700	350	35	2,700	1,350	270
Engelhard	Capital	5,300	3,000	923	6,200	3,150	820			
Engelhard	Gas/El	250	137	38	972	459	93			
McGill	Capital				6,000	3,000	1 000			
McGill	Annual				800	400	80			
Vendor Avg	Capital	5,238	2,849	876	6,325	3 005	850	5 000	2 500	500
Model	Capital	4,483	2,748	1,226	6 866	3,758	1,271	6 360	3,180	752
% Differ	Capital	17%	4%	-29%	-8%	-20%	-33%	-21%	-21%	-34%
Vendor Avg	Gas/El	180	93	24	881	434	68	2,700	1,350	270
Model	Gas/El	64	36	13	837	418	84	4 359	2,180	436
% Differ	Gas/El	-65%	-61%	-46%	-5%	-4%	24%	61%	61%	61%

All numbers are times $1 000

The numbers in table 6-3 are in $1000. The range in the model's predictions for capital expenses compared to the average capital expenses from the vendors was from -34% to 17%. This suggests a slight over prediction by the model. However, even slight differences in assumptions, such as the efficiency of the heat transfer system or the heat content of the waste stream, will result in a large shift in cost. Also, one company (Reeco) claims a new adsorption technology called Fluisorb, which is described as a polymer with greater adsorption capacity than activated carbon. The costs in the model are based on activated carbon adsorption. The better adsorption capacity will cause the model's predictions to be higher than the companies quote.

There are greater differences in the annual operating costs between the model and the vendors (-65% to 61%). One reason for the variability on annual costs is because thermal incineration is so impractical, there was only one company willing to bid on it. Having only one vendor may not accurately reflect pricing in the industry. It is important to note that the model actually predicts annual costs higher than shown in table 6-3 above, because only electricity and natural gas costs were extracted from the model. This was done because most vendors only predicted cost based on electric and gas consumption. The model actually includes other indirect annual costs such as maintenance labor, taxes, insurance and administrative costs.

The model's annual costs for the RTO system with carbon adsorption are consistently lower than the vendor's annual costs. However, because the costs are small, the percentage difference between them is exaggerated. The difference between the model and the vendors in the RTO system with carbon adsorption is caused primarily by electricity use. It is suspected that the vendors accounted for the need for auxiliary

blowers where as the model did not. Furthermore, the annual costs are still comparable between recirculation levels because the error appears to be consistent.

Air Sampling Validation

Air sampling for hexavalent chromium (Cr^{+6}) was performed at the Hill AFB C–130 painting facility on three separate occasions. The samples were taken during primer paint applications on June 9, 1997, December 11, 1997, and April 6, 1998. The Industrial Hygiene Branch of the Human Systems Center (HSC/OEMI) at Brooks AFB, TX, performed the data collection in June and December. The Analytical Services Branch (HSC/OEA) at Brooks AFB, TX, performed the data analysis for the June and December samples. Contractors from Parsons Engineering Science, Incorporated performed the data collection in April. The OSHA Salt Lake City Technical Center, UT, analyzed the samples taken in April. NIOSH Method 7600 was adhered to for all chromate sampling.

Air sampling for hexamethylene diisocyanate (HDI) was also performed at the Hill AFB painting facility on April 6, 1998. Contractor's from Parsons Engineering Science, Incorporated performed the data collection and the OSHA Salt Lake City Technical Center, UT, analyzed the samples. OSHA Method 42 was adhered to for collecting HDI samples. Table 6-4 is a summary of the all sampling data. A description of each column in table 6-4 is as follows:

- Date – date samples were taken,
- # – number of samples taken on the given date
- Analyte – type of compound analyzed,
- NIIN – paint product used at the time of air sampling (Federal Supply Class (FSC) is 8010 and all are Deft, Inc. products),
- Mix ratio – base to catalyst mixing ratio,
- % Analyte – the fraction of the analyte in the base or catalyst,
- Collected by – organization who performed the collection,

- Analysis by – organization who performed the analysis.

Table 6-4 Summary of Air Sampling

Date	#	Analyte	NIIN	Mix Ratio	% Analyte in Product	Collected by	Analysis by
9 Jun 97	3	Cr^{+6} during priming	01-416-6557	3 1	25% Strontium Chromate	HSC/OEMI Brooks AFB	HSC/OEA Brooks AFB
11 Dec 97	5	Cr^{+6} during priming	00-082-2450	1 1	25% Strontium Chromate	HSC/OEMI Brooks AFB	HSC/OEA Brooks AFB
6 Apr 98	12	Cr^{+6} during priming	01-416-6557	3 1	25% Strontium Chromate	Parsons Engineering	OSHA Salt Lake, UT
6 Apr 98	15	HDI monomer	01 305 5551	3 1	0 5%	Parsons Engineering	OSHA Salt Lake, UT
6 Apr 98	15	HDI biuret	01-305-5551	3 1	35%	Parsons Engineering	OSHA Salt Lake, UT
6 Apr 98	15	HDI polymer	01 305-5551	3 1	40%	Parsons Engineering	OSHA Salt Lake, UT

Sampling Results for Hexavalent Chromium

The results of the air sampling data for Cr^{+6} are shown in table 6-5 Each of the 22 data points represents a personal air sample The sampling cassette was attached to the collar of the painter or assistant. The dates and location that the person was primarily working are given in the second and third columns. The last two columns represent the sampling data and the model's predictions in ug/m^3 (as Cr^{+6}) No recirculation (0%) is assumed for the model's predictions because the recirculation system was not yet installed Also, 50% overspray is assumed It is also assumed that an average of 20 (maximum of 25) gallons of primer paint is used in 3 hours The model's predictions are broken into two sets because two different types of primers were used. The model's predictions are converted to Cr+6 (MW=52) from strontium chromate (MW=203 6) so that they can be compared to the Cr+6 sampling data. The following conversion formula is used

$$[Cr^{+6}]=[StrontiumChromate]*\frac{52}{203.6}$$

Table 6-5 Hexavalent Chromium Concentrations During C-130 Primer Applications

Data Point	Date	Task and Location	Sample Results ug/m³ as Cr^{+6}	Model Prediction ug/m³ as Cr^{+6}
1	6-Apr-98	Painter 1 - top wing	266	1,345
2	6-Apr-98	Painter 1 - bottom wing	792	1,345
3	6-Apr-98	Painter 2 - fuselage	1,402	1,345
4	6-Apr-98	Painter 2 - fuselage	379	1,345
5	6-Apr-98	Painter 2 - fuselage	839	1,345
6	6-Apr-98	Painter 3 - tail	619	1,345
7	6-Apr-98	Painter 3 - underbelly	1,631	1,345
8	6-Apr-98	Painter 4 - top wing	582	1,345
9	6-Apr-98	Painter 4 - bottom wing	294	1,345
10	6-Apr-98	Painter 4 - bottom wing	217	1,345
11	6-Apr-98	Assistant 2 - top wing	306	1,345
12	6-Apr-98	Assistant 2 - bottom wing	74	1,345
13	9-Jun-97	Painter 1	1,036	1,345
14	9-Jun-97	Painter 1	302	1,345
15	9-Jun-97	Painter 2	524	1,345
		Average $[Cr^{+6}]$ in ug/m³	617	1,345
		TWA/OEL (ratio)	463	1,009
16	11-Dec-97	Painter 1	274	693
17	11-Dec-97	Painter 2	176	693
18	11-Dec-97	Painter 3	183	693
19	11-Dec-97	Painter 4	1,196	693
20	11-Dec-97	Painter 5	105	693
21	11-Dec-97	Painter 6	310	693
22	11-Dec-97	Painter 7	9	693
		Average $[Cr^{+6}]$ in ug/m³	322	693
		TWA/OEL (ratio)	241	520

The average concentration for each sample set is given at the bottom of table 6-5

Also, the corresponding TWA/OEL is given below the average Assuming the painting

takes 3 hours and the ACGIH TLV-TWA is 0 5 ug/m3, the TWA/OEL is computed with the following formula

$$\frac{\text{TWA}}{\text{OEL}} = \frac{[Cr^{+6}]}{0.5\ \text{ug/m}^3}\left(\frac{3\ \text{hrs}}{8\ \text{hrs}}\right)$$

A graphical representation of the Cr^{+6} sampling data is shown in figure 6-1 The air sampling data show a wide degree of variability, which is reflective of most air sampling results. Where a worker stands, application technique, application rate, unevenly mixed air and a number of other factors add a great deal of natural variability to actual air concentrations. The model's predicted concentration is approximately twice the average air sampling results. However, three of the 20 data points are above the model's

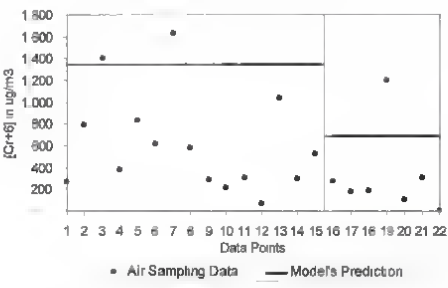


Figure 6-1 Sampling Data Versus Model Predictions for Cr^{+6} (see table 6.5)

prediction. The model corresponds well to the air sampling considering the assumptions that went into the model's predictions and the inherent variability in air sampling data. Even though the model's predictions are over the air sampling average, some over estimation is preferred

Also, the highest air sampling point can be used to compare against the model's prediction for the maximum concentration of Cr^{+6}. The highest air sampling point in the data set for Cr^{+6} is 1 631 ug/m^3 The model's predicted maximum concentration for Cr^{+6} is 1,681 ug/m^3 (adjusted from strontium chromate concentration of 6,584 ug/m^3) The model's prediction for the maximum concentration is very close to the highest observed concentration. These concentrations correspond to approximately 32 times the OSHA ceiling limit of 100 ug/m^3 (as CrO_3)

Sampling Results for HDI

Personal air samples for HDI were taken on April 6, 1998 during the polyurethane painting task. The data was collected by the contractors from Parsons Engineering Science, Incorporated and analyzed by the OSHA Salt Lake City Technical Center, UT Fifteen samples were collected on each of three forms of HDI The three forms of HDI are HDI monomer HDI biuret and HDI polymer The HDI monomer is the only chemical that has an OEL (TWA at 34 ug/m^3) and it is more significant due to its volatility In the model, it is assumed that an average of 40 (maximum of 45) gallons of polyurethane paint is used in 4 5 hours The sampling results are shown on table 6-6 in ug/m^3 The data is broken into painters (data points 1-10) and assistants (data points 11-15). The model s predictions are listed in the last row

Table 6-6 HDI Air Sampling Results

Data Point	Task and Location	HDI Sample Results HDI-monomer ug/m³	HDI-biuret ug/m³	HDI-polymer ug/m³
1	Painter 1 - fuselage	34	613	1,242
2	Painter 1 - flapwells	106	3,063	6,374
3	Painter 1 - fuselage	38	575	1,163
4	Painter 2 - flapwells	60	1,086	2,341
5	Painter 2 - fuselage	4	21	135
6	Painter 3 - top	25	763	1,475
7	Painter 3 - top	16	304	640
8	Painter 3 - underbelly	31	778	1,552
9	Painter 4 - tail	9	319	650
10	Painter 4 - tail	19	517	980
	Painter's Average	**34**	**804**	**1,655**
11	Assistant 1 - wing	ND	ND	270
12	Assistant 1 - tail	8	169	359
13	Assistant 1 - tail	9	229	475
14	Assistant 2 - fuselage	19	215	497
15	Assistant 2 - fuselage	47	592	1,249
	Assistant's Average	**21**	**301**	**570**
	Models Predictions in ug/m³	**56**	**3,915**	**4,474**

A graphical representation of the sampling data for HDI-monomer is shown in figure 6-2 Figure 6-2 shows a pattern similar figure 6-1 The model's prediction is approximately double the average sampling concentrations with a few samples above the models predictions The prediction and sampling results are similar to patterns observed in the chromium sampling The models predictions for the HDI-monomer are well within reason considering the degree of natural variability inherent to air sampling concentrations.

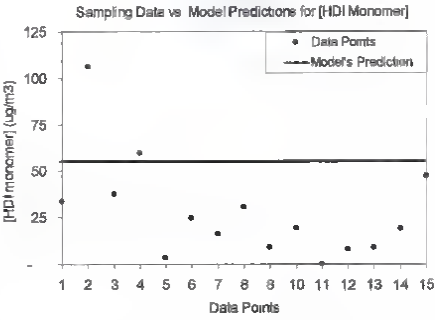


Figure 6-2 Sampling Data for HDI-Monomer (see table 6 6)

Figure 6-3 shows the sampling data and model predictions for both HDI-polymer and HDI-biuret. The model over predicts for both of these chemicals, particularly the HDI-biuret by a larger margin than previously seen. However, there is one HDI-polymer sampling point above the prediction and the over prediction is still within a reasonable margin. Also, there is controversy concerning the sampling methods used for isocyanates. Several studies argue that the isocyanate sampling methods are flawed and actual concentrations are higher than sampling results (see Hexamethylene Diisocyanate in Chapter 5 for details). This could explain some of the model s over prediction. If the actual concentrations are, in fact, higher than the sampling indicates, the model's predictions would more closely reflect the air sampling.

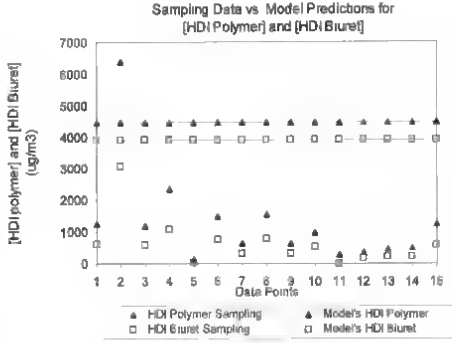


Figure 6-3 Sampling Data for HDI Polymer and Biuret (see table 6 6)

Crystal Ball Sensitivity Analysis

A sensitivity analysis was performed using Crystal Ball Version 4 0 Crystal Ball is an Excel add-on developed by Decisioneering which uses a Monte Carlo simulation technique Each variable in a spreadsheet can be given a distribution instead of a single point estimate. This allows variability and uncertainty to be taken into account in the calculations. When Crystal Ball runs a Monte Carlo simulation, a random number is selected for each variable within its distribution. This process is repeated many times computing a different outcome each time. The outputs from each iteration is computed and stored. When the simulation is complete, a distribution of outcomes is provided on a

probability distribution graph. A sensitivity analysis can then be performed which provides the level of influence each variable has on the outcome. This is a powerful tool to help understand which variable in a complex model has the greatest influence on the outcome. Then, more attention can be directed towards gathering better information about the variables that have the greatest influence on the outcome.

In this simulation, the variables listed in table 6-7 were given the corresponding point estimates. No distributions were applied to these variables. It was also assumed that there was no rinsing.

Table 6-7 Point Estimates for Sensitivity Analysis

VARIABLE	VALUE
Height of Building	11 m
Width of Building	30 m
Length of Building	30 m
TLV	1 mg/m^3
Chemicals Density (g/ml)	1 g/ml
Molecular Weight (g/mol)	100 g/mol

The sensitivity analysis was done by applying a distribution of values shown in table 6-8. Crystal Ball was allowed to run for 2000 iterations and the outcome of interest was the relative TWA. Because an OEL of 1 mg/m^3 is used, the relative TWA (unitless) is the same as the actual TWA (mg/m^3). Two Monte Carlo simulations are performed. One simulation assumes the chemical is a solid and the other assumes the chemical is a liquid. The following distributions are given to the variables.

A uniform distribution was applied to all variables except air velocity because there is a high degree of uncertainty among these variables. The uniform distribution assumes there is equal probability that any value can be selected within the given range. A

Table 6-8 Distributions for Select Variables in Sensitivity Analysis

Variable	Range	Type of Distribution
% Chemical	5 –45%	Uniform
Average Gallons Used	5-25 gal	Uniform
Overspray	30-70%	Uniform
Air Velocity	20-40 m/min	Triangular
Filter Efficiency	70-99%	Uniform
% Air Recirculated	0-99%	Uniform
Hours Product is Used	1-8 hours	Uniform

triangular distribution was applied to the air velocity because reliable air velocity measurements are available. The triangular distribution is used when there is a higher degree of certainty because less weight is given to the values near the endpoints of the range.

The sensitivity analysis results in a plot of the variables ranked by how well they correlate with the relative TWA. The correlation coefficient is used to measures how much the output variable (relative TWA) changes when the variable is changed. The correlation coefficient is a number from -1 to 1. If the correlation is close to 1, then the variable strongly influences the output variable proportionally. If the correlation is close to 0, then the variable does not substantially influence the output variable. A negative correlation means the output variable is inversely proportional to the variable (i.e. when one increases the other decreases). In other words, this analysis allows the user to see the relative impact each variable has on the relative TWA.

Sensitivity Analysis on a Solid Chemical

As can be seen in figure 6-4, the percentage of chemical in a product and the average gallons used has the greatest impact on the TWA concentration of a solid chemical. This is no surprise because these variables directly increase the mass of product

introduced to the air. The percent overspray has the next greatest impact on the TWA. The overspray impacts a solid chemical because this is the fraction that becomes airborne If the overspray is high, more mass of a solid chemical will enter the airstream. Air velocity has the next greatest impact with a negative correlation, which means as velocity increases, the TWA concentration decreases. This makes sense because increased air

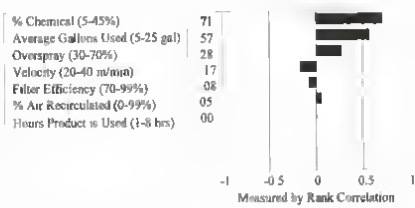


Figure 6-4 Sensitivity Analysis for Solid Chemical

velocity will pass more air through the filters designed to take out solids from the air Increased air velocity however will also increase the cost of an air control system because the airflow will increase

Filter efficiency has the next greatest impact on TWA concentrations of a solid although the correlation is weak This is surprising because computationally filter efficiency appears to have a large effect on solid chemicals There are two reasons the filter efficiency is not higher in this sensitivity analysis The impact of filter efficiency is greatest when recirculation is high. In this Monte Carlo analysis, recirculation is uniformly

distributed between 0% and 99%. During the random selections of recirculation ratios, some of the recirculation levels are low and filter efficiency has little effect. However, in reality a specific recirculation level will be selected and if it is high, filter efficiency becomes very important. Another reason filter efficiency is artificially low is because, a range of only 70% to 99% was given to filter efficiency. This assumes that some filtration will be used. The impact of filter efficiency would be greater if a wider range was given to the filter efficiency such as 0% to 99%. In fact, if the recirculation level is held fixed at 90% recirculation and a wider range of 0% to 99% is given to the filtration efficiency, the sensitivity analysis shows that filtration efficiency has the greatest influence on TWA concentration. The correlation coefficient is -0.59 for filtration efficiency and 0.58 for the percentage of chemical in the product.

The percent of air recirculated has little effect on solid chemicals because, as mentioned before, with efficient filtration much of the solids are taken out before the air is recycled. In this analysis, the range of 70% to 99% filtration efficiency is substantially high enough to limit the impact of recirculation. If no filtration is used, the percent of air recirculated would have a greater impact.

Finally, the last variable tested in this sensitivity analysis is "hours the product is used," which has virtually no effect. The reason is because the forecast variable is a TWA. If five gallons of product is used in one hour or eight hours, the average concentration over an eight-hour day remains the same. However, if the forecast variable was the maximum concentration, then the hours used would have an impact.

A probability distribution of the relative TWA for a solid chemical is provided in figure 6-5. This distribution was generated from the Monte Carlo analysis just described.

for a solid chemical. The range of the relative TWA is between 0.02 and 5.1 and the skew in the graph indicates the probability of lower concentrations is greater than upper concentrations.

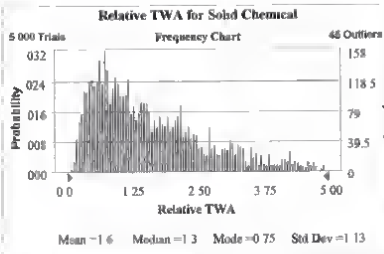


Figure 6-5 Probability Distribution for TWA of Solid Chemical

Sensitivity Analysis on a Liquid Chemical

The same variable distributions and assumptions that were used in the solid chemical analysis above were used for this sensitivity analysis for a liquid chemical. The only difference was that the phase was changed from a solid to a liquid. The results of this analysis are shown in figure 6-6. With a liquid chemical, the percent of air recirculated becomes the variable with the largest impact. As shown on figure 6-4, there is a correlation of 0.69 and this is mainly due to the fact that liquids are assumed to evaporate at 100% and bypass the filtration system. The next most important variables: percent of chemical in product, average gallons used, and air velocity are ranked the same as for a

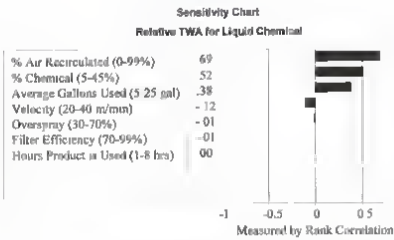


Figure 6-6 Sensitivity Analysis for Liquid Chemical

solid chemical. Overspray and filter efficiency have no impact on the TWA of a liquid chemical because it is assumed that 100% of the chemical evaporates. The number of hours the product is used has no effect because as explained above, the time it takes to apply a product does not change the average concentration over an 8-hour day. A probability distribution of the relative TWA for a liquid chemical is provided in figure 6-7. The range of the relative TWA is between 0.02 and 55, which is a much wider range than the range of outcomes for a solid.

Qualitative Sensitivity Analysis

To further understand the impact of the different variables in the model a qualitative sensitivity analysis is performed. This analysis is more subjective but it includes virtually all the variables to the model. It includes the impact on economic outputs, TWA and maximum concentrations rather than just TWA concentrations. It also

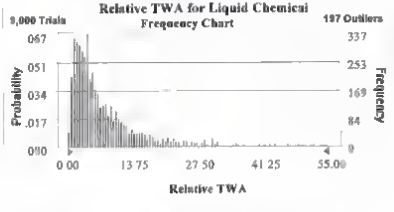


Figure 6-7 Probability Distribution for TWA of Liquid Chemical

addresses the fact that some variables are dependent on other variables which is not clearly shown in the Monte Carlo analyses due to the complex nature of the interactions.

The first column in table 6-9 shows the location of each variable in the model. Then the variable is listed in the second column followed by the outcomes indoor concentrations, operating cost of air control device and capital cost of air control device. An increasing or decreasing arrow is shown depending on the direction of the outcome (listed on top of table) relative to an increase in the variable (listed in column 2). An increasing arrow means when the variable is increased the outcome is increased and a decreasing arrow means that when the variable is increased the outcome is decreased. A dash simply means no effect. The symbol "∝" indicates a proportional relationship.

Table 6-9 Qualitative Sensitivity Analysis

Input Form	Increase to This Variable Effects >>	Air Concentrations	Operating Costs	Capital Cost
Building Form	Recirculation %	Exponential ↑	∝ linear ↓	∝ linear ↓
	Building Dimensions	magnifies effect of recirculation	∝ linear ↑	∝ linear ↑
	Air Velocity	Exponential ↓	-	
	Airflows Towards Wall or Floor	↓ or ↑ airflow, magnifies effect of recirculation	-	-
Economics Form	Natural gas price	-	near ∝ linear ↑	-
	Electricity Price	-	Small ↑	-
	Steam price	-	Small ↑ for carbon ads	Small ↑ for carbon ads
	Carbon price	-	Moderate ↑ for carbon	Moderate ↑ for carbon
	Average Indoor Temp	-	Very small ↓	-
	1st Pass Filter Efficiency 2nd Pass Filter Efficiency 3rd Pass Filter Efficiency	↓ effect of recirc on solids	↑ for larger blowers (not in this model)	↑ for larger blowers (not in this model)
	Time per Shift	↓ TWA but OEL must be adjusted	-	-
	Operating Hrs	-	near ∝ linear ↑	none
	VAPCCI Indexes	-	Inflation ↑	Inflation ↑
Task-Product-Chemical-Form	Task Time	-	-	-
	Task Times/Year	-	-	-
	Rinsed %	∝ linear ↓ (liq)	-	-
	Overspray %	∝ linear ↑ (sol)	-	-
	Wt/Vol	↑ or ↓	-	-
	Avg Usage Rate	↑ to TWA	-	-
	Max Usage Rate	↑ to Max	Small ↑	Small ↑
	Time Used	↑ to Max	-	-
	VOC Content	↑ to TWA	Small ↓	Small ↓
	Product Density	Moderate ↑	-	-
	% Chemical	↑ for chemical	-	-

CHAPTER 7
RESULTS AND CONCLUSIONS

This final chapter will discuss the results of the model's predictions concerning recirculating air at Hill AFB Painting Operations. The chemical concentration results for the maximum and TWA using OSHA OELs along with OSHA and ACGIH OELs will be discussed. Then, a fire hazard evaluation will be presented followed by economic results and other miscellaneous outputs. Finally, this chapter will present conclusions concerning the use of recirculation at the Hill AFB painting facility along with more general considerations for any facility.

Air Concentration Results

The relative maximum and TWA graphs may appear busy at first, so a simplified example with only one task is explained here. As mentioned before, the concentration predictions are normalized by dividing the concentration by the chemical's OEL. These ratios are referred to as the relative TWA or relative maximum. An example TWA chart with only one task (AF Sealer) is provided in figure 7-1. In this graph, the legend displays the task, AF Sealer, and the chemical, n,n-dimethylformamide, with the highest relative TWA within that task. The chemical, n,n-dimethylformamide, has an OSHA PEL of 30 mg/m^3. The predicted TWA concentration at 0% recirculation is 0.9 mg/m^3. The

relative TWA displayed on the graph is 0 9/30 = 0 03 The TWA concentration at 98% recirculation is 46 mg/m^3, so the relative TWA is 46/30 = 1 53 Any ratio greater than 1.0, means that the predicted concentration exceeds the OEL Also, this example graph is on a linear scale The rest of the output graphs are on a logarithmic scale for the because the actual data can vary by several orders of magnitude A logarithmic scale was used to avoid the danger of having some of the data clipped from view

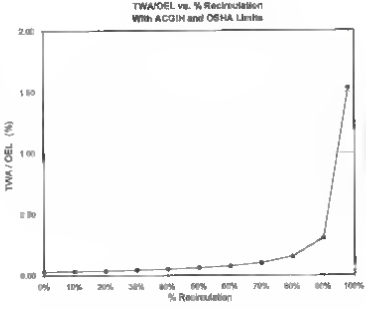


Figure 7-1 Example of Relative TWA Graph

The relative TWA and maximum graphs display how the highest chemical in each task responds to changes in the recirculation level With the relative concentration graphs to follow, all tasks are displayed on the chart unless there are no chemicals in that task with an OEL. With 17 tasks at the Hill AFB painting facility there can be many curves on

a graph. Putting all tasks on one graph was deliberate to allow the user to see the impact recirculation has to the entire operation. A table of values is also provided after the graphs to allow the user to see the values that go into each graph in more detail. Also, there are two sets of TWA and maximum graphs that follow. The first set will contain values using OSHA OELs only and the second set contains values using the most stringent of either OSHA or ACGIH OEL values

Relative Maximum Graph (OSHA Only)

Figure 7-2 is a graph of the highest relative maximum concentrations within each task. This graph represent the maximum concentration divided by the applicable OSHA ceiling limit or STEL (ACGIH not included)

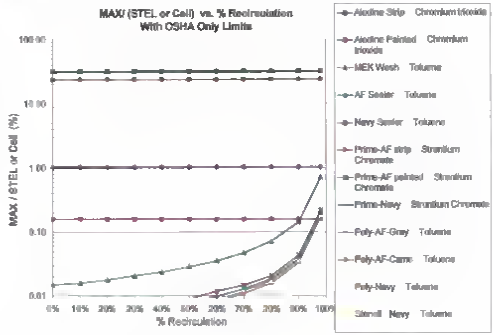


Figure 7-2 Relative Max Concentrations (OSHA Only)

As can be seen on this graph, all three tasks involving primer painting are over the OSHA ceiling limit for strontium chromate. The maximum concentrations remain relatively constant at 46, 32 and 24 times the OSHA limit for strontium chromate during these three primer tasks. The OSHA ceiling limit for chromates is 0.1 mg/m^3 and when weight adjusted for strontium chromate the limit becomes 0.2 mg/m^3 (see Regulatory Limits in Chapter 4). With a low ceiling limit and 20-35% strontium chromate in the primer paints, the limit is easily exceeded. Interestingly, the effect of varying recirculation has a negligible effect on strontium chromate concentrations. The limit for strontium chromate is exceeded even when there is no recirculation. Part of the reason that recirculation has little effect on strontium chromate concentrations is because solid chemicals like strontium chromate are filtered before the air is recirculated back into the facility. The filtration system to be installed at the Hill AFB paint facility will have two sets of filters in series so that air passes one set of filters then another set of filters. The total efficiency of the system is expected to be 99%. This efficiency virtually eliminates solids from being recycled back into the building. In fact, there is a general pattern that the concentrations of chemicals that are solids at room temperature are nearly unaffected by recirculation when high efficiency filtration is used.

During the two alodine tasks, chromium trioxide is near the ceiling limit for a stripped aircraft and at only 17% of the ceiling limit for a painted aircraft. This is because less alodine is applied to a painted aircraft. The chromate concentrations during the alodine tasks are lower than the primer applications partly because the overspray rate for the alodine task is only 10% and the overspray rate is 50% for the primer paints.

Toluene has the highest relative maximum concentration in all the other tasks and because it is a solvent that bypasses the filters, the concentrations are affected by recirculation. Toluene increases gradually at first then more rapidly as recirculation increases. The highest relative concentrations of toluene are during the MEK wash task. However, the toluene does not exceed the ceiling limit even at the higher recirculation rates.

Relative TWA Graph (OSHA Only)

The relative TWA graph using OSHA PELs is shown in figure 7-3. This graph shows several tasks exponentially increasing in concentration as recirculation increases. The upper three curves, which all start just above the OSHA PEL involve the

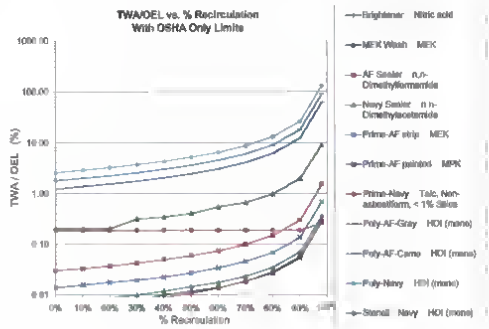


Figure 7-3 Relative TWA Concentrations (OSHA Only)

polyurethane painting tasks. The chemical involved is the free monomer form of hexamethylene diisocyanate (HDI) There is generally a 4-fold increase in relative TWA concentrations from 0% to 75% recirculation. The OSHA PEL for HDI-monomer is 0 034 mg/m^3 and it is treated as a liquid because it is volatile It should be noted that all the MSDSs for the polyurethane paints indicated < 0 5% HDI-monomer As a conservative assumption, the input to the model was 0 5% even though it is likely that the actual amount of HDI-monomer is less than 0 5% Actual concentrations of HDI-monomer are likely to be less than the model's predictions In fact, one study which analyzed paints from five different manufacturers showed that the paints contained 30 to 36% HDI-polymer but only 0 19 to 0 32% HDI-monomer (Rosenburg and Tuomi, 1984 119).

Virtually all other tasks on the relative TWA graph are increasing exponentially with recirculation and all the chemicals involved are liquids that will evaporate regardless of filtration. The highest task among these liquids is the Air Force Sealer task involving the chemical n, n-Dimethylformamide, which has an OSHA PEL of 30 mg/m^3 This chemical exceeds the PEL only at the 98% level and all other chemicals are predicted to remain below their respective OSHA PELs in the other tasks. Table 7-1 lists the concentration data generated by the model, which was used to create both the "OSHA Only" graphs (figures 7 2 and 7-3)

Red Lines in Graphs – Chemical Change

If a chemical with the highest relative maximum or TWA concentration changes at some level of recirculation, a red line will appear on the curve The red line indicates that a different chemical now has the highest relative concentration at that level of

Table 7-1 Relative MAX and TWA Concentration Data (OSHA Only)

HIGHEST MAX/CEIL and TWA/OEL for OSHA ONLY														
Task	Recirculation Level											1° Chemical	OEL
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	98%		mg/m³
	Max/STEL												
Alodine Strip	1	1	1	1	1	1	1 1	1 1	1 1	1 1	1 1	CrO3	0 1
Alodine Painted	0 2	0 2	0.2	0 2	0 2	0.2	0.2	0.2	0.2	0.2	0.2	CrO3	0 1
MEK Wash	0.01	0.02	0.02	0.02	0 02	0 03	0.04	0.05	0 07	0 15	0 73	Toluene	1120
AF Sealer								0 02	0 02	0 04	0.2	Toluene	1128
Navy Sealer								0 02	0 03	0 04	0.22	Toluene	1128
Prime-AF strip	23 0	23 0	24 0	24 0	24 0	24 0	24 0	24 1	24 1	24 1	24.2	Stront Cr	0.204
Prime-AF paint	31 0	32 1	32.3	32 5	32 4	32 6	32 8	33 1	33 2	33.3	33 4	Stront Cr	0.204
Prime-Navy	31.2	31.3	31 3	31 3	31 4	31 4	31 4	31 5	31 5	31 5	31 6	Stront Cr	0.204
Poly AF-Gray						0.01	0.01	0.01	0.01	0 04	0 18	Toluene	1128
Poly-AF-Camo						0 01	0 01	0 01	0 01	0 03	0.16	Toluene	1128
Poly-Navy						0 01	0 01	0 01	0 01	0 03	0 17	Toluene	1128
	TWA/OEL												
Brightener	0 01	0.01	0 01	0.01	0 01	0 01	0 02	0 02	0 04	0 07	0 36	Nitric acid	5
MEK Wash	0 01	0 01	0 01	0.01	0.01	0 01	0 01	0 02	0 03	0 06	0 29	MEK	590
AF Sealer	0 03	0 03	0.04	0 04	0 05	0.06	0 08	0 1	0 15	0.31	1 53	MPK	700
Navy Sealer	0 01	0 01	0 01	0 01	0.01	0.01	0 02	0.02	0.04	0 07	0 36	n,n-dimethyl formamide	35
Prime-AF strip	0 02	0 02	0 02	0 02	0 02	0 03	0 03	0 05	0 07	0 14	0 7	MEK	590
Prime-AF paint	0 01	0 01	0 01	0 01	0 01	0 01	0 01	0 02	0 03	0 06	0.28	MPK	700
Prime-Navy	0 19	0 19	0 19	0 19	0 19	0 19	0 19	0 19	0 19	0 19	0.27	Talc < 1% Silica	2
Poly-AF-Gray	1 24	1.39	1.55	1 77	2.07	2 49	3 11	4 15	6.22	12.4	62.1	HDI (Mono)	0.034
Poly-AF-Camo	1 82	2 01	2.26	2.60	3 02	3 63	4 55	6.04	9 10	18.1	90.2	HDI (Mono)	0 034
Poly-Navy	2 62	2.93	3 29	3 75	4.37	5.28	6.59	8 76	13.1	26 3	131	HDI (Mono)	0 034
Stencil-AF											0 02	MIBK	410
Stencil - Navy	0.21	0.21	0.21	0.32	0 35	0 41	0.56	0 67	0.99	1 99	9.13	HDI (Mono)	0.034

recirculation. For example, in figure 7-3, under the Prime-Navy task, there is a red line at the end of the curve between 90% and 98%. This red line indicates that the chemical that had the highest relative TWA from 0% to 80% recirculation has changed to a different chemical at 90% recirculation. The highest chemical was talc, non-asbestiform from 0% to 80% recirculation but it was surpassed at 90% and 98% recirculation by methyl ethyl ketone.

Because the model only plots the highest relative chemical within each task, the red line was added to signal when there is a change in the chemical. So in the example above, talc, non-asbestiform is listed in the legend under the Prime-Navy task because it had the highest relative TWA at 0% recirculation. A chemical switch will not be noted in the legend, due to space limitations. However, the user will be alerted that a chemical change has occurred when a red line in shown in the graph. The user can go to the spreadsheet named "Top 4 Chem" to view the top four chemicals in that task. This will allow the user to see more detailed chemical concentration data within a specific task. The "Data" spreadsheet can also be manipulated by changing the recirculation level to identify the chemical and product that has the highest relative concentration.

Relative Maximum Graph (OSHA and ACGIH)

Figure 7-4 is a graph of the highest relative maximum and TWA concentrations with respect to the applicable ceiling limit or STEL according to OSHA or ACGIH (whichever is most conservative). Several features on this relative maximum graph are similar to the "OSHA only" relative maximum graph discussed above. The uppermost three lines correspond to the three primer applications, which is the same as the "OSHA only" graph because the same OSHA limit for strontium chromate (0.2 mg/m^3) is used. Also, the two alodine processes are the same as the "OSHA only" graph. These primer and alodine processes involve chromate solids and are nearly unaffected by recirculation because filtration eliminates much of the chromate solids before the air is recirculated.

The rest of the tasks on the relative maximum graph involve liquids that increase exponentially with the recirculation level. The curves for the three polyurethane and two

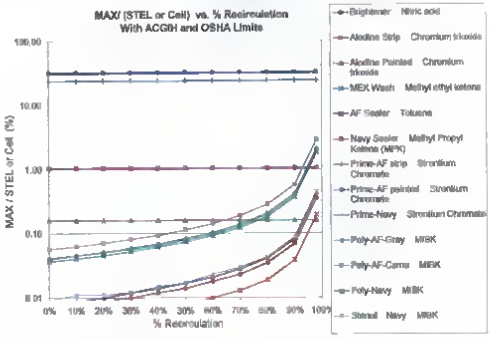


Figure 7-4 Relative Maximum Concentrations (OSHA and ACGIH)

stencil tasks have shifted upwards when ACGIH OELs are taken into account The reason for this is because ACGIH has a STEL of 307 mg/m^3 for methyl isobutyl ketone (MIBK) found in the polyurethane paints whereas OSHA does not have a STEL for MIBK MIBK has a higher relative maximum concentrations than the toluene concentrations found in the "OSHA Only" graph (figure 7-2) The three polyurethane tasks and the MEK wash process exceed the applicable ceiling at the 98% recirculation level but are below the ceiling levels below 95% recirculation. The curves for the two sealer tasks and the brightener task also shift upwards due to lower ceilings limits when ACGIH OELs are applied

Relative TWA Graph (OSHA and ACGIH)

Figure 7-5 is a graph of the highest relative TWA concentrations with respect to both OSHA PELs and ACGIH TLVs (whichever is most conservative). Perhaps the most striking result of this graph is the three primer tasks which are predicted at roughly 750 (AF strip), 1000 (AF painted) and 1000 (Navy) times the ACGIH limit for Strontium Chromate. There is no OSHA PEL for strontium chromate only an OSHA ceiling limit However, the ACGIH TLV for strontium chromate is 0 0005 mg/m^3 (as Cr), which is 0 002 mg/m^3 when weight adjusted for strontium (see Chapter 4, Regulatory Limits for calculations)

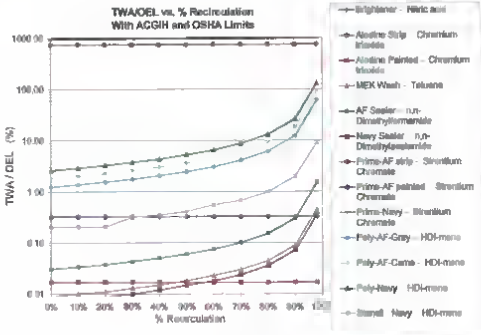


Figure 7-5 Relative TWA Concentrations (OSHA and ACGIH)

To gain a better understanding as to why this concentration can be so relatively high, a calculation will be performed below It only takes a TWA concentration of 2 mg/m^3 of strontium chromate to exceed the 0 002 mg/m^3 limit by 1000 times For example, the navy primer paint contains 25 % strontium chromate and the average application rate of primer paint is five gallons/hour Assume the overspray is 50%, the product density is 1 3 mg/ml and there is no recirculation. The steady state concentration derived in chapter 3 is given below The formula is multiplied by the overspray because overspray effects solid concentrations such as strontium chromate. S is the source concentration and Q_t is the total flow rate The steady state concentration is as follows

$$C(\infty) = \frac{S * \text{Overspray}}{Qt}$$

where Q_t – 10,065 m^3/min

$$S = \frac{mg}{min} = \%\ \text{by wt} * \text{Gal/hr} * \rho_{prod} * 63{,}067$$

$$C(\infty) = \frac{25\% * 5\ \text{gal/hr} * 1\ 3\ \text{mg/ml} * 63{,}067 * 50\%}{10{,}065\ \text{m3/min}} = 5\ \text{mg/m3}$$

The Navy primer paint is used for three hours so the TWA in an 8-hour day can be estimated at 5 mg/m^3 * (3/8) = 1 9 mg/m^3. This TWA is about 1000 times the ACGIH limit of 0 002 mg/m^3 with no recirculation at all. Air sampling results for hexavalent chromate taken at this facility, also show concentrations reaching up to 1000 times the ACGIH TLV (see Air Sampling in Chapter 6)

An important feature in this graph is that the effect of recirculation is negligible during the primer applications From a recirculation of 0% to 98%, the relative TWA changes for the Prime AF – Paint task is from 1008 to 1018 times the TLV This is a 1% change in concentration, which corresponds to the filtration efficiency of 99% The filtration efficiency is the most important parameter when evaluating solid particles at high recirculation rates. The percent increase in concentration for solids is roughly (1 – filter efficiency) when recirculation is near 100%

With the relative TWA for strontium chromate so high, other chemicals can be masked because the graph only shows the highest chemical per task. A further evaluation of the primer tasks using the "Top 4 Chem" sheet, which displays the top four chemicals in any selected task, shows that in the Prime AF-strip task, methylene bisphenyl isocyanate (MDI) is also high MDI had a relative TWA of 7.2 (ACGIH TLV = 05 mg/m^3), and it was also nearly unaffected by recirculation. Also masked by the high strontium chromate levels is silica, cristobalite during the Prime-Navy task It had a nearly constant relative TWA at 7 7 (ACGIH TLV=0 05, OSHA PEL=30 mg/m^3) across all recirculation levels The MDI and silica cristobalite are solids and are therefore nearly unaffected by recirculation.

Also in the relative TWA graph (figure 7-5) the three polyurethane tasks remain the same as the TWA graph for OSHA only (figure 7-3) The HDI-monomer is increasing with respect to recirculation in these three polyurethane tasks (see discussion in TWA graph for OSHA only)

The two alodine are now on the TWA graph when ACGIH TLVs are taken into account because chromium trioxide has an ACGIH TLV of 0 01 mg/m^3 whereas OSHA

does not have a PEL for chromium (OSHA has a ceiling only) However, the alodine tasks are nearly unaffected by recirculation.

The two sealer tasks are the same with or without the ACGIH TLVs because OSHA and ACGIH agree on a TWA for the highest chemicals which are n,n-dimethylacetamide and n,n-dimethylformamide The MEK wash task shifts upwards because the ACGIH limit for toluene is 188 mg/m^3 versus OSHAs limit of 750 mg/m^3 This shifts the highest chemical in the MEK wash from MEK to toluene when ACGIH limits are used A curve for the brightener task can not be seen in this graph because the values are exactly the same as the Navy-Sealer task.

The Navy stencil task is the same with or without ACGIH OELs because both OSHA and ACGIH agree on the TWA limit for HDI-monomer The AF stencil task is shifted upwards because the ACGIH TLV for MIBK is 205 mg/m^3 and the OSHA PEL is 410 mg/m^3 giving a higher relative TWA for MIBK. Table 7-2 lists the relative maximum and TWA concentration data used to create the graphs in figures 7-4 and 7-5

General Trends in Concentration Data

There was a general trend noticed in most of the concentration data where liquid chemicals are concerned There is a gradual increase in concentrations followed by a more dramatic increase The concentrations generally doubled at 50% recirculation, increased by five times at 80%, 10 times at 90% and 50 times at 98% This trend may not always hold true If airflow was lower or building volume was smaller the lag effect in concentration would become more significant and the trends may not be the same

Table 7-2 MAX/Ceil and TWA/OEL Data for ACGIH and OSHA

HIGHEST MAX/CEIL and TWA/OEL for ACGIH and OSHA														
Task	Recirculation Level											1st Chemical	OEL
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	98%		
MAX/STEL													
Brightener	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.04	0.08	0.42	Nitric acid	10
Alodine Strip	1	1	1	1	1	1	1.1	1.1	1.1	1.1	1.1	CrO3	0.1
Alodine Painted	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	CrO3	0.1
MEK Wash	0.04	0.04	0.05	0.05	0.06	0.07	0.09	0.12	0.19	0.37	1.85	MEK	885
AF Sealer							0.01	0.02	0.02	0.04	0.2	MEK	1120
Navy Sealer	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.07	0.35	MPK	881
Primo-AF strip	23.9	23.9	24.0	24.0	24.0	24.0	24.1	24.1	24.1	24.1	24.2	Stronl Cr	0.286
Primo-AF paint	32.3	32.4	32.4	32.4	32.5	32.5	32.5	32.6	32.6	32.6	32.7	Stronl Cr	0.294
Primo-Navy	31.2	31.3	31.3	31.3	31.4	31.4	31.4	31.5	31.5	31.5	31.6	Stronl Cr	0.294
Poly-AF-Gray	0.04	0.05	0.05	0.06	0.07	0.08	0.1	0.14	0.21	0.42	2.1	MIBK	307
Poly-AF-Camo	0.06	0.06	0.07	0.07	0.1	0.11	0.14	0.18	0.28	0.57	2.84	MIBK	307
Poly-Navy	0.04	0.04	0.04	0.06	0.06	0.08	0.1	0.13	0.2	0.4	2.03	MIBK	307
Stencil-AF										0.01	0.03	MIBK	307
Stencil Navy	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.06	0.43	MIBK	307
Soil Barrier											0.02	PGME	553
TWA/OEL													
Brightener	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.07	0.36	Nitric acid	5
Alodine Strip	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	CrO3	0.096
Alodine Painted	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	CrO3	0.096
MEK Wash	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.05	0.09	0.45	Toluene	188
AF Sealer	0.03	0.03	0.04	0.04	0.05	0.06	0.08	0.1	0.15	0.31	1.53	n,n-dimethyl formamide	30
Navy Sealer	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.04	0.07	0.36	n,n-dimethyl acetamide	35
Primo-AF strip	747	748	748	749	750	751	751	752	753	754	754	Stronl Cr	0.002
Primo-AF paint	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	Stronl Cr	0.002
Primo-Navy	974	975	976	977	978	979	980	981	982	983	984	Stronl Cr	0.080
Poly-AF-Gray	1.24	1.39	1.6	1.8	2.1	2.5	3.1	4.2	6.2	12.4	62.1	HDI (Mono)	0.034
Poly-AF-Camo	1.8	2.0	2.3	2.6	3.0	3.6	4.6	6.04	9.1	18.2	90.2	HDI (Mono)	0.034
Poly-Navy	2.6	2.9	3.3	3.8	4.4	5.3	6.6	8.8	13.3	26.0	131	HDI (Mono)	0.034
Stencil-AF										0.01	0.04	MIBK	205
Stencil Navy	0.2	0.2	0.2	0.3	0.3	0.4	0.6	0.7	1.0	2.0	9.1	HDI (Mono)	0.034

The percent increases followed a pattern that is shown in table 7-3 Also, a 10 times increase in concentration may not matter much if the relative concentration is very small in relation to the OEL. The pattern in the percent increases is shown in table 7-3 Also, the trend follows the steady state concentration formula derived in Chapter 3 If the emission

source and the total flow rate are constant, the modified formula below can be a good general rule of thumb Co is the concentration with 0% recirculation.

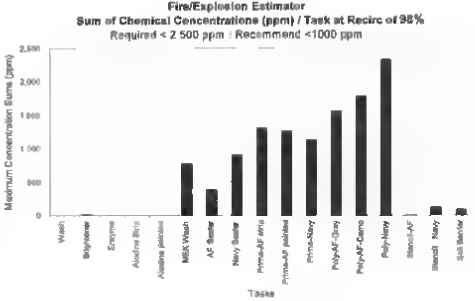
$$C(\%\,\mathrm{Rec}) = \frac{Co}{(1 - \%\,\mathrm{Rec})}$$

Table 7-3 General Trends in Concentration Data

General Trends in Data			
Recirculation Increment	% Increase in Concentration	Cumulative Recirculation	% Increase in Concentration
0% – 10%	10%	0% -10%	10%
10% – 20%	13%	0% -20%	25%
20% – 30%	15%	0% -30%	40%
30% – 40%	15%	0% -40%	70%
40% – 50%	20%	0% -50%	100%
50% 60%	25%	0% -60%	150%
60% – 70%	30%	0% -70%	200%
70% – 80%	50%	0% -80%	400%
60% 90%	100%	0% -90%	900%
90% – 98%	400%	0% -98%	5000%

Fire/Explosion Estimator

Figures 7-6a and 7-6b, illustrate another model output concerning the fire/explosion hazard at the 98% and 90% recirculation levels. As recirculation increases, so does the threat of a fire hazard. As a way of estimating the fire hazard, it is assumed that the total quantity of a product will contribute to the fire hazard. The maximum concentration in each task is calculated by summing the maximum concentration of every product in that task (see Lower Explosive Limit in Chapter 2 for more detail) The results are then plotted on a graph similar to the ones shown in figures 7-6a and 7-6b. When the recirculation level is at 98% (figure 7-6a), the highest concentration occurs during the



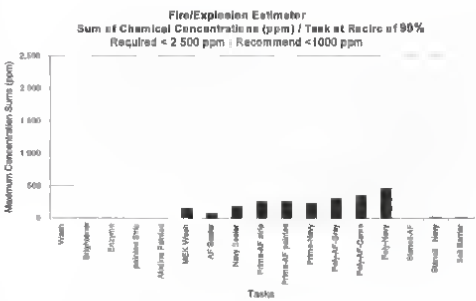


Figure 7-6 Fire Hazard Maximum Concentration in PPM a) at 98% and b) at 90% Recirculation

Navy Polyurethane task with a potential maximum of 2,300 ppm. Because most chemicals have a lower explosive limit (LEL) of 1% (10,000 ppm) OSHA requires that concentrations be kept below 25% of the LEL (see chapter 2) and 10% is recommended Therefore, the concentration must not exceed 2,500 ppm and preferably less than 1 000 ppm. While the highest concentration of 2,300 ppm is below the required maximum of 2 500 ppm, this is close enough to be a concern because the risk of an explosion is so devastating At 90%, shown in figure 7-6b, the highest concentration, which is during the Navy polyurethane task drops from 2300 ppm to 465 ppm. This calculation is only an estimate and localized higher concentrations within the building or ductwork could buildup making the potential for an explosive hazard even greater Also, chemicals with a lower LEL may be used instead of the assumed 1%. It would therefore be prudent to keep recirculation below 75% due to uncertainties in the fire hazard A recirculation level of 75% provides a more comfortable cushion to protect against the threat of a fire or explosion caused by chemical build-up A more detailed fire hazard analysis is necessary to be sure 25% of the LEL is not exceeded at higher levels of recirculation.

Economic Outputs

The economic outputs are illustrated in two different ways: Cumulative Costs over 10 years and Annualized Costs The 10 year cumulative costs assumes the initial capital costs are spent in year 0, then the annual operating costs are added incrementally each year over the next 10 years. It is assumed that the control systems have a 10-year lifetime The cumulative costs are based on a specific recirculation rate Figures 7-7a and 7-7b

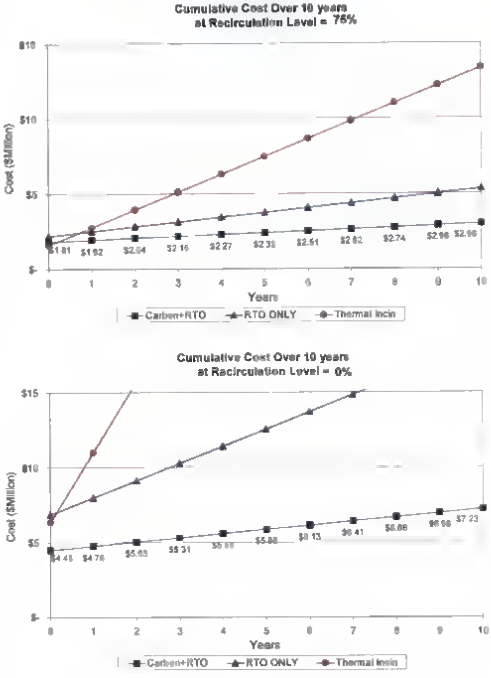


Figure 7-7 Air Control Costs Over 10 Years. a) at 75% and b) at 0% Recirculation

pertain to 75% and 0% recirculation rates. The lowest cumulative cost over 10 years in both cases is the RTO with carbon adsorption. The data labels on the chart correspond to the RTO with carbon adsorption curve. Initially, there is a $2.68 million difference between the 75% recirculation and 0% recirculation. After 10 years, there is a $4.25 million difference.

The other way the model graphs cost is on an annualized basis as shown in figure 7-8. This is an economic principle that spreads the capital cost of the system across the lifetime of the system into equal annualized costs. It does not reflect actual annual payments but it puts uneven annual costs into a single number so that comparisons can be made. This allows the user to compare costs versus various levels of recirculation rather

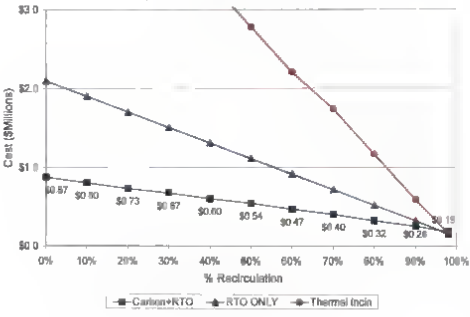


Figure 7-8 Annualized Cost at Various Recirculation Levels

than just selecting one recirculation level. As can be seen in figure 7-8, the technologies with the higher cost have a more dramatic difference in annualized cost with changes in recirculation. However, the RTO with carbon adsorption still has a substantial drop from $870,000 annually at 0% to $320,000 annually at 80% ($550,000 annual savings)

Miscellaneous Outputs

Another useful graph for environmental management purposes is the VOC Output by task shown in figure 7-9 This graph allows the user to see a breakdown of which tasks produce the bulk of the VOCs. The total output of VOCs from the Hill AFB painting facility is 30,421 lbs/year The task with the greatest output at this facility is the

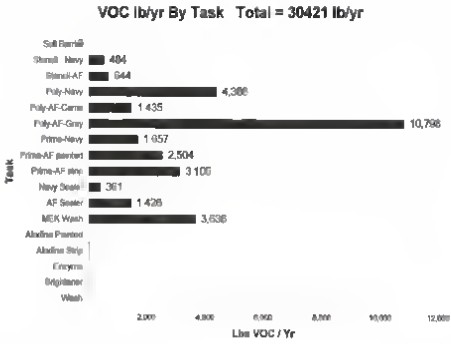


Figure 7-9 VOC Lbs/Yr by Task

"Poly-AF-gray" with 10,798 lbs/year of VOCs being output accounting for 36% of the total. This makes sense because 36 of the 50 planes painted in this facility are Air Force with a gray paint scheme. The next highest task is the "poly-Navy" task with an output of 4,366 lbs/year. This is followed by the MEK Wash task at 3 638 lbs/year. An environmental manager can look more closely at the tasks contributing the greatest amount of VOCs to reduce the VOC emissions from this facility. Perhaps different polyurethane paints could be substituted to reduce overall emissions.

Another useful graph is the annual hours/task graph shown in figure 7-10. It gives a breakdown of the annual number of hours per task. Of the 4,047 annual hours accounted for at the Hill AFB painting facility, 1920 hours (47%) is spent with Air Force stenciling followed by 720 hours (18%) spent with Navy stenciling. All other tasks

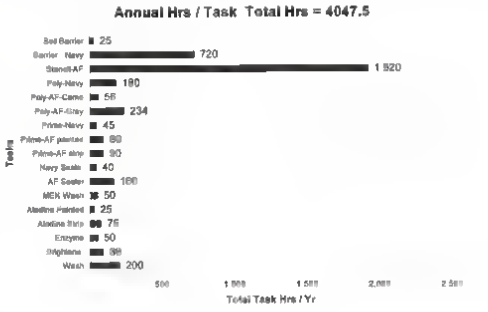


Figure 7-10 Annual Hours Per Task

require less time comparatively This chart can also help in the decision making over recirculation. At the Hill AFB painting facility over half of the time is spent stenciling which outputs the least amount of relative concentrations. The amount of time a worker spends in a hazardous environment is not supposed to be used when interpreting OSHA or ACGIH data because the limits are based on an 8-hour day, 40-hour workweek However if large concentrations are produced during tasks that occur infrequently, perhaps other alternatives could be entertained such doing the task outside when feasible

Recommendations

The following section will provide some recommendations for the Hill AFB painting facility that can also be applied to other industrial sites considering recirculating industrial air Recirculation is only one option to reduce compliance costs. Due to the fact that recirculating industrial air will increase indoor air concentrations, it is prudent to consider other more desirable options first. For example switching to low VOC paints would eliminate the requirement and the expense of destroying VOCs. In reducing compliance costs, process modifications or product substitutions should always be considered first before recirculation is considered. At the Hill AFB painting facility these options are not practical due to aircraft maintenance requirements and poor adhesion with low VOC paints

A recirculation of 75% or less is recommended for the Hill AFB painting facility The increases in concentrations for all chemicals are modest up to about 75% After 75% the concentrations begin to increase more rapidly The highest chemical that is effected by recirculation is the HDI-monomer during the polyurethane tasks The increases in relative

TWA concentration for HDI from 0 to 75 % recirculation is 2 6 to 10 5 However, the strontium chromate concentrations during the primer painting can reach 1000 times the OEL and is unaffected by recirculation. Therefore, the level of protection needed for the primer tasks will provide adequate protection for the HDI-monomer concentrations during the polyurethane tasks. The capital cost of a VOC control device using the RTO with carbon adsorption technology is $4 48 million and $1 8 million at 0% and 75% recirculation respectively (saving $2 68 million). The annual operating cost is $116,000 at 75% and $237,000 with no recirculation (saving $121,000 annually)

It is strongly recommended that the respirators used in the Hill AFB painting facility be upgraded to a pressure-demand, full-face respirator The respirators currently used at the facility are continuous flow hoods, which have an assigned protection factor (APF) of 25 The APF for different types of respirators are given in AFOSH Standard 48-1, Appendix 4 (AFOSH 48-1, 1996) which was written to comply with OSHA's respiratory protection regulation 29 CFR 1910 134 (OSHA, 1997b). A selection from the Air Force Standard is shown in table 7-4 below A pressure-demand, full-face respirator provides an APF of 1000 This level of protection is needed due to the potentially high concentrations of hexavalent chromium during the primer tasks.

This recommendation for enhanced respiratory protection is not due to the anticipation of recirculation but due to the high levels of chromate predicted in the model and verified during air sampling (see Air Sampling in Chapter 6). Diligent use of personal protective equipment such as respirators is critical to the safety of workers. Qualitative and quantitative respiratory fit-tests and employee training on proper use and care of respirators should be conducted regularly

Table 7-4 Respirator Assigned Protection Factors

ATMOSPHERE SUPPLYING	Assigned protection factor
Any supplied-air respirator equipped with a loose-fitting hood or helmet or loose-fitting face piece and operated in the continuous flow mode	25
Any supplied-air respirator equipped with a half mask and operated in a pressure demand or continuous flow mode	50
Any supplied-air respirator equipped with a full face piece and operated in continuous flow mode	50
Any supplied-air respirator equipped with a full face piece and operated in pressure demand mode.	1000

It is also recommended that highly efficient filtration be installed (above 98% total filtration efficiency) At a recirculation rate of 75%, it is important to keep the chromates and other solids from re-entering the indoor air The solid chemicals are the greatest health threat at the Hill AFB painting facility Recirculation will have virtually no effect on the concentrations of solids if an efficient filtration system is used, properly maintained and tested. Devices to continuously monitor the filtration system are needed to be sure the filters have not been breached allowing particles to pass through (i.e. holes in the filters or improperly installed filters allowing air gaps) It may be desirable to install pre-filters over main filters to reduce the frequency and cost of having to change the main filters. Also, airflow needs to be continuously monitored to prevent blockage or overloaded filters from hindering the airflow which will allow chemicals to buildup

LEL monitors should be installed at strategic locations in the duct system and in the building to warn of a potential fire hazard. An automatic shutdown of the recirculation unit allowing 100% fresh air needs to be installed so the system can quickly compensate if a fire hazard is detected. Intrinsically safe equipment should be used in areas with a potential for reaching the lower explosive limit

At the Hill AFB facility, the brightener solution contains nitric and phosphoric acid, which may create the need for a supplemental acid control system. The use of any caustic products may require the need for additional pre-treatment. An air scrubber located before the VOC control device may be required to prevent damage to the air control system.

If carbon adsorption is used, thermal detection devices may be necessary in the carbon bed to prevent bed fires. Localized high temperatures can occur in a carbon bed resulting in a fire when ketones or organic acids are adsorbed (see chapter 3 for more information).

Most importantly, a comprehensive air sampling program should be required to validate the actual air concentrations in the building before and after a recirculation system has been installed. Approval to use the recirculation system should be dependent on air sampling results. After a recirculation system is installed, a routine sampling program should be established to periodically check indoor air concentrations. Many factors such as product changes, poorly maintained filters, equipment changes, or a change in application rates can alter indoor air concentrations.

Even after recirculation is implemented, efforts to reduce worker exposures should be continued. For example, in painting operations product substitutions for the primer and polyurethane paints can have a significant reduction in potential exposures. Substituting primers that contain less strontium chromate and polyurethane paints that contain less HDI should reduce the concentrations of these chemicals. During this analysis, it was observed that a primer paint being used at the Hill AFB facility was changed from a primer containing 15% strontium chromate to a primer containing 30% strontium chromate. The

change went unnoticed because the manufacturer simply reformulated the paint Manufacturer reformulation can occur often without changing the products name or stock number Primers with the least amount of strontium chromate should be used. A long-term solution is a chromate free primer or at least a primer paint that contains some other chromate salt such as magnesium chromate, potassium dichromate or zinc chromate These other chromate compounds have an ACGIH TLV 100 times higher than strontium chromate This indicates that these other chromate compounds are safer alternatives then strontium chromate. A continued search for safer products is always an intelligent approach.

Process modifications can reduce indoor concentrations as well. At the Hill AFB painting facility the paint guns are cleaned after each application by flushing one or two gallons of MEK or thinner through the gun The product rinsate is collected as hazardous waste but it is still an emission source and creates a waste problem. At Edwards AFB a fully enclosed paint gun-cleaning unit, which recycles the cleaning fluid has been implemented to clean paint guns with virtually no emissions. One source for the enclosed cleaning units is Gun Wash Unit made by Graco (Model 112-638) at (800) 328-0211

Conclusions

The objective of this research to develop a computer model to assess cost and worker safety relative to recirculating industrial air is completed Also, the objective of performing a case study at Hill AFB C-130 painting operations to validate and demonstrate the model is completed. Recirculating industrial air has serious ramifications that should not be taken lightly If not properly designed adverse conditions could

endanger workers' health. If the system is properly designed and all tasks are taken into consideration, recirculating some fraction of the air can be done safely and cost effectively. At the Hill AFB C-130 painting facility, recirculating 75% of the air has a negligible impact on workers' health and can save $2.68 million in capital costs.

Using the model created in this dissertation to help visualize the impact of recirculation along with good sound judgement should result in a better decision concerning the use of recirculation. Data entry into the model is made easy with a user friendly windows environment and an interactive chemical database containing over 1300 chemicals. This helps to ensure the model becomes a useful tool when contemplating recirculation or during industrial hygiene evaluations. There is a risk taken when tedious hand calculations are performed on "selected products." Some overlooked products may be a major health threat and go unnoticed.

Other models designed to predict air concentrations are based on saturation vapor pressure, which yield unrealistic results. This model was created in Excel, which is a familiar spreadsheet format to allow the user to manipulate the output data as needed. After the model creates the output data, all formulas are stored in Excel so the user can determine how certain calculations are performed. A fully illustrated user's manual written in Word 97 also facilitates the use of the model.

GLOSSARY

ACGIH	American Conference of Governmental Industrial Hygienists
AFB	Air Force Base
AFOSH	Air Force Occupational Safety and Health
ANSI	American National Standards Institute
APF	Assigned Protection Factor
ATSDR	Agency for Toxic Substances and Disease Registry
BEE	Bioenvironmental Engineering
CAAA	Clean Air Act Amendment
CAS	Chemical Abstract Services Registry Number
Ceiling Level	The chemical concentration that should not be exceeded during any part of the work exposure set by either OSHA or ACGIH
cfm	cubic feet per minute
HAP	Hazardous Air Pollutant
HDI	hexamethylene diisocyanate
IUPAC	International Union of Pure And Applied Chemistry
LEL	Lower Explosive Limit – the lowest concentration at which an ignition source can ignite a fire
MEK	methyl ethyl ketone
MACT	Maximum Achievable Control Technology
MIBK	methyl isobutyl ketone
MPK	methyl propyl ketone
NESHAP	National Emission Standards for Hazardous Air Pollutants
NIOSH	National Institute of Occupational Safety and Health
NIIN	National Item Identification Number
OSHA	Occupational Safety and Health Administration
OEL	Occupational Exposure Limit – general term to describe all limits
PEL	Permissible Exposure Limit – The time weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which all workers may be repeatedly exposed, day after day without adverse effect. Set by OSHA.
PGME	propylene glycol monomethyl ether
STEL	Short Term Exposure Limit – a 15 minute TWA exposure which should not be exceeded at any time during a workday even if the 8-hour TWA is within the TLV TWA. Exposures up to the STEL shall not occur more than four times/day and must be separated by at least one hour. Set by ACGIH and OSHA
TLV	Threshold Limit Value – The time weighted average concentration for a conventional 8-hour workday and a 40-hour workweek, to which all workers may be repeatedly exposed, day after day without adverse effect. Set by ACGIH

TWA	Time Weighted Average
VBA	Visual Basic for Applications
VOC	Volatile Organic Compound

APPENDIX
PRODUCT LIST

The products used in each task are described by

- Name – Name of the Product,
- NIIN – National Item Identification Number
- Prod Hrs – average number of hours that the product is used within the task,
- Avg Gal – average gallons of product used in that task,
- Max Gal – maximum gallons of product used in that task,
- AvgGPH – average gallons/hour application rate
- Overspray – Fraction that becomes airborne (not adhered to part)
- Rinse – Fraction that is rinsed away, unavailable to evaporate into the air

TASK/Product	NIIN	Prod Hrs	Avg Gal	Max Gal	Over spray	Rinse
Wash						
Soap	P1879-G	4	12 5	25	10%	95%
Brightener						
Brightener	003009008	3 5	25	25	10%	95%
Enzyme						
Enzyme	P-901380F	2	5	5	10%	95%
Alodine Strip						
Alodine Strip	008238039	3	80	100	10%	90%
Alodine Painted						
Alodine Painted	008238039	1	4	5	10%	90%
MEK Wash						
MEK Only	002900046	1	5	6	50%	N/A
1:1 Toluene: MEK	002900046	1	5	6	50%	N/A
AF Sealer						
1432 – Gray Seal Comp, 1 of 2	003443666	2	3	3	N/A	N/A
1432 – Gray Seal Comp, 2 of 2	003443666	2	1	1	N/A	N/A
1436 – Gray Seal Comp, 1 of 2	008718489	2	3	3	N/A	N/A
1436 – Gray Seal Comp, 2 of 2	008718489	2	1	1	N/A	N/A

TASK/Product	NIIN	Prod Hrs	Avg Gal	Max Gal	Over spray	Rinse
MEK	002812763	4	1 5	1 5	N/A	N/A
Toluene	002900046	4	1 5	1 5	N/A	N/A
Walkway Comp- 36231	006410426	2	4	4	N/A	N/A
AF Primer	012137898	2	0 5	0.5	N/A	N/A
Navy Sealer						
1436 – Gray Seal Comp, 1 of 2	008718489	2	3	3	N/A	N/A
1436 – Gray Seal Comp, 2 of 2	008718489	2	1	1	N/A	N/A
MEK	002812763	2	0.75	0 75	N/A	N/A
Toluene	002900046	2	0 75	0 75	N/A	N/A
Walkway Comp – 35237	PG-6651	2	12	12	N/A	N/A
Navy Primer 1 of 2	010486539	2	0 75	1 5	N/A	N/A
Navy Primer 2 of 2	010486539	2	0.25	0 5	N/A	N/A
Prime-AF strip						
AF Strip Primer (8 1)	012137898	3	17 8	22.2	50%	N/A
Korflex Accel 2 of 2	P910X7510B	3	2.2	2.8	50%	N/A
Poly Thinner	002801751	1	5	6	50%	N/A
MEK	002812763	1	5	6	50%	N/A
Prime-AF painted						
AF Strip Primer 1 of 2	014166557	3	15	18 75	50%	N/A
AF Strip Primer 2 of 2	014166557	3	5	6 25	50%	N/A
Poly Thinner	002801751	1	5	6	50%	N/A
MEK	002812763	1	5	6	50%	N/A
Prime-Navy						
Navy Primer 1 of 2	010486539	3	15	18 75	50%	N/A
Navy Primer 2 of 2	010486539	3	5	6 25	50%	N/A
Poly Thinner	002801751	1	5	6	50%	N/A
MEK	002812763	1	5	6	50%	N/A
Poly-AF-Gray						
Gray Poly 36173 1 of 2	013456535	4 5	30	37 5	50%	N/A
Gray Poly 36173 2 of 2	013456535	4 5	10	12.5	50%	N/A
Poly Thinner	002801751	2	10	12	50%	N/A
MEK	002812763	2	10	12	50%	N/A
Poly-AF-Camo						
Gray Poly 36118 1 of 2	013055551	6	33 75	37 5	50%	N/A
Gray Poly 36118 2 of 2	013055551	6	11.25	12 5	50%	N/A
Green Poly 34102, 1 of 2	013363036	4	7 5	7 5	50%	N/A

TASK/Product	NIIN	Prod Hrs	Avg Gal	Max Gal	Over spray	Rinse
Green Poly 34102 2 of 2	013363036	4	2.5	2.5	50%	N/A
Green Poly 34092 1 of 2	013363034	4	7.5	7.5	50%	N/A
Green Poly 34092, 2 of 2	013363034	4	2.5	2.5	50%	N/A
Poly Thinner	002801751	2	10	12	50%	N/A
MEK	002812763	2	10	12	50%	N/A
Poly-Navy						
Lt Gray Poly 36495, 1 of 2	012659149	4	33.75	33.75	50%	N/A
Lt Gray Poly 36495 2 of 2	012659149	4	11.25	11.25	50%	N/A
Med Gray Poly 1 of 2	012659152	4	15	15	50%	N/A
Med Gray Poly, 2 of 2	012659152	4	5	5	50%	N/A
Dk Gray Poly 35237 1 of 2	012659140	4	15	15	50%	N/A
Dk Gray Poly 35237, 2 of 2	012659140	4	5	5	50%	N/A
Poly Thinner	002801751	2	10	12	50%	N/A
MEK	002812763	2	10	12	50%	N/A
Stencil-AF						
Flat Black Poly 1 of 2	012853554	28	3	3.75	50%	N/A
Flat Black Poly 2 of 2	012853554	20	1	1.25	50%	N/A
Stencil – Navy						
Lt Gray Poly 36495, 1 of 2	012659149	24	2.25	3	50%	N/A
Lt Gray Poly 36495, 2 of 2	012659149	24	0.75	1	50%	N/A
Med Gray Poly 1 of 2	012659152	24	2.25	3	50%	N/A
Med Gray Poly, 2 of 2	012659152	24	0.75	1	50%	N/A
Dk Gray Poly 35237, 1 of 2	012659140	24	2.25	3	50%	N/A
Dk Gray Poly 35237, 2 of 2	012659140	24	0.75	1	50%	N/A
Red Poly 11136 (props) 1 of 2	012659154	8	0.5	0.5	50%	N/A
Red Poly 11136 (props), 2 of 2	012659154	8	0.5	0.5	50%	N/A
White Poly 17925 (props) 1 of 2	012659143	8	0.5	0.5	50%	N/A
White Poly 17925 (props), 2 of 2	012659143	8	0.5	0.5	50%	N/A
Silver Epoxy (flap wells) 1 of 2	PEEBA005A	3	2.25	3	50%	N/A
Silver Epoxy (flap wells) 2 of 2	PEEBA005A	3	0.75	1	50%	N/A
Soil Barrier						
Soil Barrier	012714099	0.5	0.5	0.5	50%	N/A

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BIOGRAPHICAL SKETCH

Peter T LaPuma was born and raised in upstate New York. He obtained a BS in Mechanical Engineering in 1986 at Clarkson University, Potsdam, NY, under an Air Force ROTC scholarship. He met his wife, Cheryl, while in college and they were married in 1987. They now have two boys named Michael and Nathan.

He joined the Air Force upon graduation in 1986. From 1986-1990 he worked at the Armstrong Labs, Human Systems Division located at Wright-Patterson AFB, OH. He was a research engineer in an optical research branch. While at the lab, he designed and oversaw the manufacture of over 40 experimental devices involved in optical research.

Peter earned a master's degree in business administration in 1991 at Wright State University, OH. From 1990 to 1993, he was the Director of Industrial Hygiene in the Bioenvironmental Engineering Office at Wright-Patterson AFB. From 1993 to 1994, he attended the Air Force Institute of Technology, OH, and earned a master's degree in environmental engineering. His research involved designing an infrared detection system to study soil desorption of trichloroethylene, a solvent found in the groundwater of several AF bases.

From 1994-1995, he worked at the Environics Lab at Tyndall AFB, FL, as an environmental engineering research officer. He managed 13 environmental research programs with an $8 million budget. In 1995, he was selected for a Ph.D. scholarship in environmental engineering with a follow-on assignment in 1998 as a faculty member at the Air Force Institute of Technology at Wright-Patterson AFB, OH. He was promoted to Major on March 1, 1998.

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